International
Energy Agency

Renewable Energy
TECHNOLOGIES

Solar Energy Perspectives

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In 90 minutes, enough sunlight strikes the earth to provide the entire planet's energy needs for one year. While solar energy is abundant, it represents a tiny fraction of the world's current energy mix. But this is changing rapidly and is being driven by global action to improve energy access and supply security, and to mitigate climate change.

Around the world, countries and companies are investing in solar generation capacity on an unprecedented scale, and, as a consequence, costs continue to fall and technologies improve. This publication gives an authoritative view of these technologies and market trends, in both advanced and developing economies, while providing examples of the best and most advanced practices. It also provides a unique guide for policy makers, industry representatives and concerned stakeholders on how best to use, combine and successfully promote the major categories of solar energy: solar heating and cooling, photovoltaic and solar thermal electricity, as well as solar fuels.

Finally, in analysing the likely evolution of electricity and energy-consuming sectors – buildings, industry and transport – it explores the leading role solar energy could play in the long-term future of our energy system.

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INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 28 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

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The European Commission also participates in the work of the IEA.

International Energy Agency

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“The sun will be the fuel of the future”

Anonymous, 1876, *Popular Science*

Foreword

Solar energy technologies have witnessed false starts, such as the early boom of solar water heaters in California a century ago, and the renewed interest that followed the first and second oil shocks. Will they now fulfil their promise to deliver affordable, abundant, inexhaustible and clean energy? Which solar technologies are really close to competitiveness, in which circumstances and for which uses? What kind of policy support do they require and for how long? What are the costs, who will bear them? What are the benefits, and who will reap them?

The rapid evolution of these technologies makes policy answers to those questions unusually difficult. Up to now, only a limited number of countries have been supporting most of the effort to drive solar energy technologies to competitiveness. Concerns about costs have also sometimes led to abrupt policy revisions. Policies may lapse or lose momentum just a few years before they would have succeeded.

This timely publication is the first in-depth IEA technology study focusing on renewable technologies. It offers relevant information, accurate data and sound analyses to policy makers, industry stakeholders, and the wider public. It builds upon the *IEA Energy Technology Perspectives* in considering end-use sectors and the ever-growing role of electricity. It also builds on many *IEA Technology Roadmaps* in elaborating an integrated approach to various solar energy technologies. It shows how they could combine to respond to our energy needs in providing electricity, heat and fuels.

This publication also investigates ways to make support policies more effective and cost-effective. It suggests that comprehensive and fine-tuned policies supporting a large portfolio of solar energy technologies could be extended to most sunny regions of the world, where most of the growth of population and economy is taking place. If this were the case, solar energy could well become a competitive energy source in many applications within the next twenty years.

In the penultimate chapter, this publication departs from usual IEA work and complements our least-cost modelling exercises by depicting a world in which solar energy reaches its very fullest potential by the second part of this century. A number of assumptions are made to see what might be possible in terms of solar deployment, while keeping affordability in sight. Under these assumptions, solar energy has immense potential and could emerge as a major source of energy, in particular if energy-related carbon dioxide emissions must be reduced to quite low levels and if other low-carbon technology options cannot deliver on large scale. While this outcome is hypothetical, it does suggest that current efforts are warranted to enrich the portfolio of clean and sustainable energy options for the future.

Maria van der Hoeven
Executive Director

This publication has been produced under the authority of the Executive Director of the International Energy Agency. The views expressed do not necessarily reflect the views or policies of individual IEA member countries.

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Executive Summary

This publication builds upon past analyses of solar energy deployment contained in the *Word Energy Outlook, Energy Technology Perspectives* and several *IEA Technology Roadmaps*. It aims at offering an updated picture of current technology trends and markets, as well as new analyses on how solar energy technologies for electricity, heat and fuels can be used in the various energy consuming sectors, now and in the future.

If effective support policies are put in place in a wide number of countries during this decade, solar energy in its various forms – solar heat, solar photovoltaics, solar thermal electricity, solar fuels – can make considerable contributions to solving some of the most urgent problems the world now faces: climate change, energy security, and universal access to modern energy services.

Solar energy offers a clean, climate-friendly, very abundant and inexhaustible energy resource to mankind, relatively well-spread over the globe. Its availability is greater in warm and sunny countries – those countries that will experience most of the world's population and economic growth over the next decades. They will likely contain about 7 billion inhabitants by 2050 *versus* 2 billion in cold and temperate countries (including most of Europe, Russia, and parts of China and the United States of America).

The costs of solar energy have been falling rapidly and are entering new areas of competitiveness. Solar thermal electricity (STE) and solar photovoltaic electricity (PV) are competitive against oil-fuelled electricity generation in sunny countries, usually to cover demand peaks, and in many islands. Roof-top PV in sunny countries can compete with high retail electricity prices. In most markets, however, solar electricity is not yet able to compete without specific incentives.

Technology trends

The dynamics of PV deployment have been particularly remarkable, driven mostly by feed-in tariffs. PV is extremely modular, easy and fast to install and accessible to the general public. With suitably established policies and mature markets and finance, PV projects can have short lead times. The rapid cost reductions driven by this deployment have confirmed earlier expectations related to the learning rate of PV. They have also increased confidence that sustained deployment will reduce costs further – if policies and incentives are adjusted to cost reductions, but not discontinued.

Solar thermal electricity (STE) allows shifting the production of solar electricity to peak or mid-peak hours in the evening, or spreading it to base-load hours round the clock, through the use of thermal storage. Fuel back-up and hybridisation with other resources help make it reliable and dispatchable on demand, and offer cheaper options for including solar energy in the electricity mix.

STE today is based on concentrating solar power (CSP) technologies, which can be used where the sun is very bright and the skies clear. Long-range transmission lines can transport clean STE from favourable areas (*e.g.* North Africa) to other large consuming areas (*e.g.* Europe). As such, STE complements PV rather than competing with it. Today, large-scale PV plants emerge, though one important advantage of PV is that is can be built close to consumers (*e.g.* on building roofs). STE lends towards utility-scale plants, but small-scale STE may find niche markets in isolated or weak grids. Firm and flexible STE capacities enable more variable renewable energy (*i.e.* wind power and solar PV) in the electricity mix on grids. While very high penetration of PV requires large-scale investment in electricity storage, such as pumped-hydro plants, high penetration of STE does not.

Off grid in developing countries, solar PV and STE can transform the lives of those 1.4 billion people currently deprived of access to electricity, and those who can barely rely on their grid. Solar cooking and solar water heating can also provide significant contribution to raise the living standards in developing economies. Even in countries with well developed energy systems, solar technologies can help ensure greater energy security and sustainability.

End-use sectors

The largest solar contribution to our energy needs is currently through solar heat technologies. The potential for solar water heating is considerable. Solar energy can provide a significant contribution to space heating needs, both directly and through heat pumps. Direct solar cooling offers additional options but may face tough competition from standard cooling systems run by solar electricity.

Buildings are the largest energy consumers today. Positive-energy building combining excellent thermal insulation, smart design and the exploitation of free solar resources can help change this. Ambient energy, *i.e.* the low-temperature heat of the surrounding air and ground, transferred into buildings with heat pumps, solar water heating, solar space heating, solar cooling and PV can combine to fulfil buildings' energy needs with minimal waste.

Industry requires large amounts of electricity and process heat at various temperature levels. Solar PV, STE and solar heating and cooling (SHC) can combine to address these needs in part, including those of agriculture, craft industry, cooking and desalination. Solar process heat is currently untapped, but offers a significant potential in many sectors of the economy. Concentrating solar technologies can provide high-temperature process heat in clear-sky areas; solar-generated electricity or solar fuels can do the job elsewhere. More efficient end-use technologies would help make electricity a primary carrier of solar energy in industry.

Transportation is the energy consuming sector that is most difficult to decarbonise – and it is the most dependent on highly volatile oil prices. Solar and other renewable electricity can contribute significantly to fuel transport systems when converted to electricity. The contribution from biofuels can be enhanced by using solar as the energy source in processing raw biomass.

In countries with bright sunshine and clear skies, concentrating solar technologies enable the production of gaseous, liquid or solid fuels, as well as new carriers for energy from fossil feedstock, recovered CO_2 streams, biomass or water. Solar-enhanced biofuels would have a smaller carbon footprint than others. Solar fuels could be transported and stored, then used for electricity generation, to provide heat to buildings or industry and energy for transport.

A possible vision

Earlier modelling exercises at the IEA have been seeking for the least-cost energy mix by 2050 compatible with cutting global energy-related CO_2 emissions by half from 2005 levels. The High-Renewable scenario variant showed that PV and STE together could provide up to 25% of global electricity by 2050. In such carbon-constrained scenarios, the levelised cost of solar electricity comes close to those of competitors, including fossil fuels, at about USD 100/MWh by 2030.

This publication elaborates on these findings, looking farther into the second half of this century. It assumes that greenhouse gas emissions will need to be reduced to significantly lower levels. It assumes that electricity-driven technologies will be required to foster energy efficiency improvements and displace fossil fuels in many uses in buildings, industry and transportation. It finally tests the limits of the expansion of solar energy and other renewables, in case other low-carbon energy technologies are themselves limited in their expansion for whatever reason. After 2030, these limits are not mainly determined by the direct generation costs of solar energy, but rather by its variability, footprint (land occupied), and the lower density and transportability of solar compared to fossil fuels.

Under all these strong assumptions, a long-term energy mix dominated by solar energy in various forms may or may not be the cheapest low-carbon energy mix, but it would be affordable. In sunny and dry climates, solar thermal electricity will largely be able to overcome variability issues thanks to thermal storage. In the least sunny countries, as well as in sunny and wet climates, the variability of PV electricity and wind power will need to be addressed through a combination of grid expansion, demand-side management, hydro power, pumped hydro storage and balancing plants. The footprint (land occupied) of solar energy will raise challenges in some densely populated areas when all possibilities offered by buildings are exhausted, but is globally manageable. In these circumstances, and provided all necessary policies are implemented rapidly, solar energy could provide a third of the global final energy demand after 2060, while CO_2 emissions would be reduced to very low levels.

Policy needs

A broad range of policies will be needed to unlock the considerable potential of solar energy. They include establishing incentives for early deployment, removing non-economic barriers, developing public-private partnerships, subsidising research and development, and developing effective encouragement and support for innovation. New business and financing models are required, in particular for up-front financing of off-grid solar electricity and process heat technologies in developing countries.

The number of governments at all levels who consider implementing policies to support the development and deployment of solar energy is growing by the day. However, few so far have elaborated comprehensive policy sets. Public research and development efforts are critically needed, for example, in the area of solar hydrogen and fuels. Policies to favour the use of direct solar heat in industry are still rare. Principal-agent problems continue to prevent solar heating and cooling to develop in buildings, obstacles to grid access and permitting hamper the deployment of solar electricity, financing difficulties loom large. The recent growth in instalment is too concentrated in too few countries.

The early deployment of solar energy technologies entails costs. Support policies include a significant part of subsidies as long as solar technologies are not fully competitive. They must be adjusted to reflect cost reductions, in consultation with industry and in as predictable a manner as possible. Incentive policies must not be abandoned before new electricity market design ensures investments in competitive solar energy technologies, grid upgrades, storage and balancing plants.

The development of affordable, inexhaustible and clean solar energy technologies will have huge longer-term benefits. It will increase countries' energy security through reliance on an indigenous, inexhaustible and mostly import-independent resource, enhance sustainability, reduce pollution, lower the costs of mitigating climate change, and keep fossil fuel prices lower than otherwise. These advantages are global. Hence the additional costs of the incentives for early deployment should be considered learning investments; they must be wisely spent and need to be widely shared.

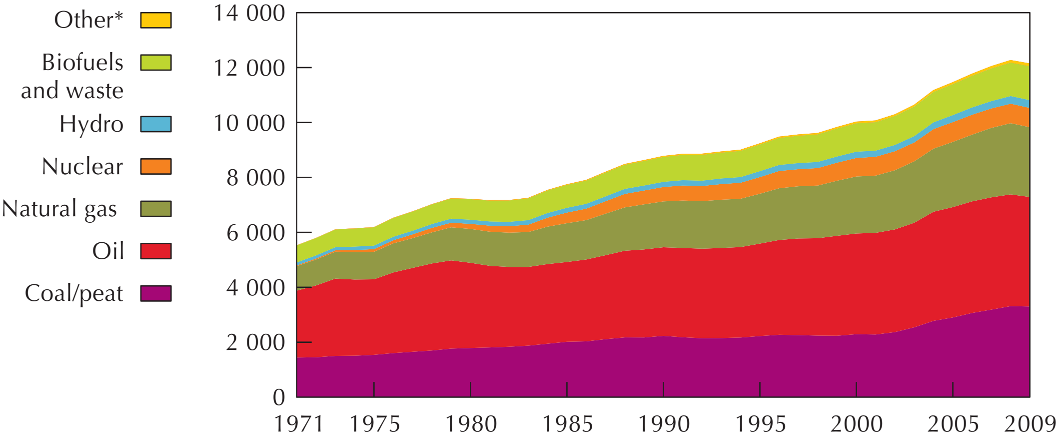
Chapter 1
Rationale for harnessing the solar resource

Solar energy has huge potential and its use is growing fast, yet in many quarters it is still viewed with concern about costs and doubts over efficacy. All countries and economies stand to gain by understanding solar energy's potential to fill a very large part of total energy needs economically, in a secure and sustainable manner in the future. It can also help to reduce the greenhouse gases (GHGs) that threaten irreversible climate change for the planet.

Solar energy has been the fastest-growing energy sector in the last few years, albeit from a very low basis. It is expected to reach competitiveness on a large scale in less than ten years – but today most applications require support incentives, the cost of which is a serious concern for some policy makers. Some see solar energy as a boost for economic growth, others as a drag in the aftermath of a global financial crisis and in the context of sovereign debts. Solar energy currently does little to abate GHG emissions, but it will play an important and ever-growing role in climate-friendly scenarios in the coming decades.

Nevertheless, solar energy still barely shows up in recent energy statistics (Figure 1.1). Even among renewable sources, direct uses of solar energy are outpaced by biomass, hydropower and wind – three forms of renewable ultimately powered by the sun growing crops, evaporating water and creating the pressure differences that cause wind (Figure 1.2).

Figure 1.1 **Evolution of world total primary energy supply (Mtoe)**



*Note: *Other includes geothermal, solar, wind, heat, etc.*

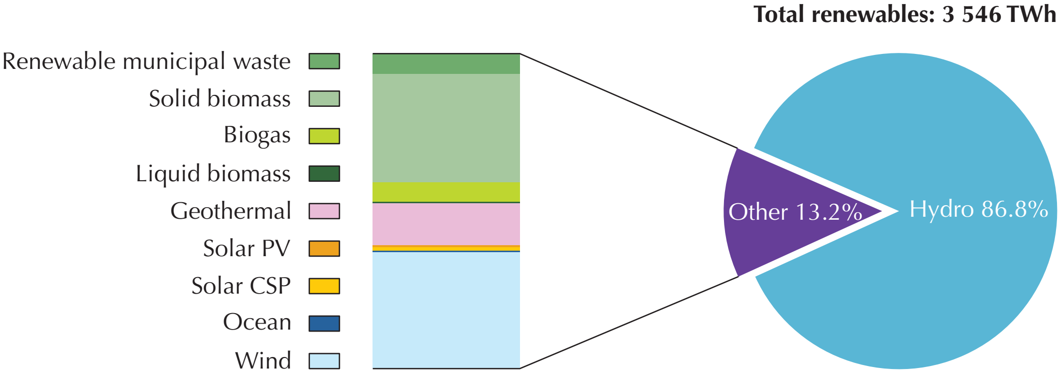
Source: IEA, 2011a.

Key point

At present, only a tiny portion of solar energy's potential is used.

In one sense, the low penetration of solar is because economic analyses do not account for the many benefits sunshine provides to humanity: keeping the earth's surface temperature on average around 15°C; evaporating water; nourishing crops and trees; drying harvests and clothes; illuminating our days; making our skin synthesize vitamin D3; and many others. But, even overlooking these factors, the question remains: *Why are free and renewable energy forms still largely outpaced by costly fossil fuels, which are less widespread and are exhaustible?*

Figure 1.2 **Renewable electricity generation in 2007**



Source: IEA, 2010a.

Key point

Direct solar electricity still pales next to other renewables.

For millennia, solar energy and its derivatives – human force, animal traction, biomass and wind for sailing – were the only energy forms used by humans. Coal and (naturally seeping) oil were known, but played a very small role. During the Middle Ages, watermills and windmills became more common, so renewable energy was still dominant. From around 1300, however, the use of coal for space heating increased, and became dominant in the 17th century in the British Isles. Steam engines and coal-based metallurgy developed in the 18th century. Town gas, made from coal, was used for lighting in the 19th century, when subsoil oil, primarily to be used for lighting, was discovered.

At the beginning of the 20th century, while incandescent bulbs and electricity from hydropower and coal burning began displacing oil for lighting, the emergence of the auto industry provided a new market for oil products. Nowadays, fossil fuels – oil, coal and gas – provide more than 80% of the world's primary energy supply. By contrast, all renewable energies together comprise about 13%.

This domination of fossil fuels needs an explanation. Year after year, decade after decade, the fossil fuel industry has maintained dominance and resisted competition by new entrants. Its advantage is built on two practical factors: density and convenience.

Fossil fuels are very dense in energy. One litre of gasoline can deliver 35 megajoules of energy – twice as much as one kilogram of wood. This is the amount of energy one square metre of land receives from the sun in the best conditions in approximately ten hours. Plus, gasoline is easy to handle, store and transport, as are all fuels that are liquid at ordinary temperature and pressure.

Solid fuels like coal, and gaseous fuels like natural gas, are less convenient. Still, they have greater energy content – per mass unit – than wood, the main source of heat before their emergence. Like oil, they are remnants of ancient living organisms[1] initially powered, directly or indirectly, by solar energy through photosynthesis. Collected and concentrated along food chains, then accumulated and cooked under great pressure by geological processes for aeons, fossil fuels obtain considerable energy density.

The challenge for collecting renewable energy is to do so in a manner so efficient and cheap that its obvious advantages – it is inexhaustible, most often not import-dependent and does not pollute much – fully compensate for the initial disadvantage of lesser convenience. The relatively low density of most renewable energy flows compounds this challenge. However, prospects for reaching competitive levels have improved dramatically in the last few years. And the highest energy density of all renewables by land surface area is offered by direct solar conversion into heat or electricity, and possibly fuels.

Drivers and incentives

There are many reasons for developing and deploying solar energy while fossil fuels still dominate the global economy's energy balance. Its ubiquity and sustainability mean that it is among the most secure sources of energy available to any country, even in comparison to other renewable sources of energy. It is also one of the least polluting. Along with other renewables, it can drastically reduce energy-related GHG emissions in the next few decades to help limit climate change. Other important drivers are the desires of people, cities and regions to be less dependent on remote providers of energy and to hedge against fossil-fuel price volatility.

Fossil resources are finite. However, it is difficult to predict when their scarcity will by itself raise their prices so high that most alternatives would become less costly in the current state of technologies. Except for the original continental-US "peak oil" prediction by King Hubbert in 1956, all global forecasts have been proven wrong – so far. Oil shocks have been followed by gluts, high prices by low prices. The ratio between proven oil reserves and current production has constantly improved, from 20 years in 1948 to 46 years in 2010.

However, to maintain this record in the decades to come, oil will need to be produced in ever more extreme environments, such as ultra-deep water and the arctic, using more sophisticated and expensive unconventional technologies, very likely keeping costs above USD 60 per barrel, which is twice the average level fewer than ten years ago. While short-term fluctuations in supply and demand and low price elasticity mean that spot prices will continue to gyrate, rising average prices are inevitable. The era of cheap oil seems over. Furthermore, price volatility raises valid concerns, as does a hefty dependence on too few producing countries.

The availability of natural gas has recently been augmented by shale gas exploitation, and there are huge and wide-spread coal reserves available to generate electricity. At less than USD 100/bbl, gas and coal can also be transformed into liquid fuels. But there are well-known environmental concerns with the extraction and processing of both these fuels and

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[1] *Except, maybe, for some methane that may be produced by abiotic phenomena.*

CO_2 emissions associated with the manufacture of liquids from coal are even larger than those associated with their burning, unless captured at manufacturing plant level and stored in the ground.

Scarcity risks and volatile prices thus offer significant motives to move away from fossil fuels, but for many the most imperative driver remains climate change mitigation. As Sheikh Zaki Yamani, a former oil minister of Saudi Arabia, once said, "the Stone Age did not end for lack of stones". In the *World Energy Outlook* (IEA, 2010*b*), the most climate-friendly scenario suggests that global oil production could peak around 2015, falling briskly thereafter, as a result of weaker demand driven entirely by policy, and *not* by geological constraint (as demonstrated by contrast in the other scenarios).

The atmosphere has been subject to a considerable increase in concentration of the trace gases that are transparent to light and opaque to heat radiations, therefore increasing the greenhouse effect that keeps the earth warm. The climate change issue is plagued with many uncertainties, but these concern the pace and amplitude of man-made increased greenhouse effect, not its reality.

At the 2010 United Nations Climate Change Conference (Cancun, Mexico), the international community formally agreed to limit global warming to 2°C from the pre-industrial level, and to consider (by 2013 to 2015) a possible strengthening of this objective to limit global warming to 1.5°C. But the current obligations accepted by most industrialised countries under the Kyoto Protocol, and the new pledges made at the occasion of the climate conference held in 2009 in Copenhagen by the United States and several large emerging economies, are unlikely to be enough to limit global warming to these levels and stabilise our climate. The difficult challenge ahead of climate negotiators is to persuade countries to adopt more ambitious objectives.[2]

The BLUE Map Scenario of the IEA *Energy Technology Perspectives 2010* (*ETP* 2010), and the 450 Scenario of the IEA *World Energy Outlook 2010* (*WEO* 2010), aim to illustrate the deep changes in the energy sector that would lead to emission paths broadly compatible with limiting global warming to 2°C if the climate sensitivity of the planet has the value scientists believe most likely (IEA, 2010*a* and IEA, 2010*b*). These scenarios drive global energy-related CO_2 emissions to peak at the end of this decade at the latest, and to achieve a halving of 2005 levels by 2050.

Renewable energy plays a significant role in these scenarios and represents a large potential for emission reductions, second only to energy efficiency improvements. Until 2035, it will also have greater impact than other potential alternatives including both carbon dioxide capture and storage (CCS) or nuclear power. Solar energy, *i.e.* solar photovoltaics, concentrating solar power and solar heating, are the energy technologies exhibiting the fastest growth in these scenarios. The two former combined are projected to provide more than 10% of global electricity by 2050 (IEA, 2010*a*). Indeed, solar photovoltaics have witnessed the most rapid growth of any energy technology in the last ten years, although from a very narrow base. Deployment more than doubled in 2010 despite the global financial and economic crisis – largely as a result of incentive policies.

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*[2] A sensible strategy, possibly easier to share globally in a context of uncertainties with regard to mitigation costs, could be to set ambitious objectives, but accept that countries will stay on track only as long as the costs of these cuts remain acceptable (IEA, 2008*a*).*

More significantly perhaps, in scenarios that call for a more rapid deployment of renewables, such as the *ETP 2010* "Hi-Ren" (for high-renewable) scenario, solar energy makes the largest additional contribution to GHG emission cuts, probably because of its almost unlimited potential. Solar electricity tops 25% of global electricity generation by 2050, more than either wind power or hydro power. By contrast, most other renewables – with the possible exception of wind power – may meet some kind of intrinsic limits. If this is the case, in a carbon-lean world economy solar energy would continue to grow faster than any other energy resource long after 2050. Solar energy is particularly available in warm and sunny countries, where most of the growth – population, economy, and energy demand – will take place in this century. Warm and sunny countries will likely contain about seven billion inhabitants by 2050, *versus* two billion in cold and temperate countries (including most of Europe, Russia and parts of China and the United States).

An important implication of these scenario analyses is that, if other important technologies or policies required to cut emissions fail to deliver according to expectations, a more rapid deployment of solar energy technologies could possibly fill the gap. Energy efficiency is essential but growth in demand, the so-called "rebound effect",[3] might be underestimated; nuclear power may face greater political and public acceptance difficulties; CCS is still under development.

Furthermore, according to the Intergovernmental Panel on Climate Change (IPCC, 2007), a reduction of GHG emissions by 2050 of 50% from 2 000 levels is only the minimum reduction required to keep the long-term increase of global temperatures to within 2°C to 3°C. Reductions of up to 85% might be needed to keep within these temperature rises. This would imply that CO_2 emissions should be constrained to less than 6 Gt CO_2 in 2050 and beyond. As *ETP 2010* put it, "a prudent approach might be to identify a portfolio of low-carbon technologies that could exceed the 50% reduction target in case deeper cuts are needed or some of the technological options identified do not become commercially available as originally thought." This publication therefore outlines an energy future with very little CO_2 emissions and small contributions from technologies other than renewables.

This is not to say that renewable energies, and solar in particular, will not face expected and unexpected challenges. They already do. In 2011, policy makers in several European countries expressed legitimate worries about the "excessive success" of their policies on solar photovoltaics (PV). Based on incentives per kilowatt-hours (kWh) for long periods of time – typically 20 years – these policies create long-lasting liabilities for electricity customers and sometimes taxpayers.

The incentives appear too generous, often only months after they have been set. This results from the very rapid cost decrease of PV – an effect precisely in line with the goals of the policy. Roof-mounted PV modules are now competitive, not only off-grid, but also on grid in sunny countries with high retail electricity prices. Cost concerns are legitimate, but it would be foolish to give up at this stage. Market expansion drives cost reductions, and cost cuts expand niche markets, which sets in motion a virtuous circle. Nothing indicates that this development would meet any limit soon, but the impetus still requires policy support for a few more years.

Despite the costs, deploying renewables gives policy makers a positive, industrialising, job creating, and non-restrictive means of action to mitigate climate change. While European policy

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[3] *Energy efficiency improvements reduce energy consumption and thus the costs of doing anything; as a result, people might do more of it. For example, they may drive longer distances with more efficient cars.*

makers struggle to reduce incentive levels as fast as PV costs fall, policy makers in Algeria, Chile, China, India, Japan, Morocco, South Africa and others set up new policy targets and implement new policy tools to deploy renewables faster, develop competitive clean-energy industries and ultimately "green their growth". The politically optimal mix of options to ensure energy security and reduce greenhouse gas may not exactly coincide with the economically optimal, least-cost mix that models suggest. Yet, renewable energy appears, well beyond Kyoto, as the most secure means to stabilise the climate, and solar energy might become the prime contributor.

Structure of the book

Besides its Executive Summary and the current chapter, this book is divided into three sections. Part A considers markets and outlook for solar energy from a demand-side point of view, for electricity generation, buildings, industry and transport. Part B assesses in more detail the state of the art of mature and emerging solar technologies. Part C offers insights into the way forward.

Part A. Markets and outlook

Chapter 2 considers the huge solar resource and its distribution over time and space. It briefly introduces the technologies that capture and use energy from the sun.

Chapter 3 examines the forthcoming role of solar in generating electricity – in a world that is likely to need ever more of it. Solar electricity from photovoltaic and solar thermal could equal hydro power and wind power by 2050 or before, and surpass them in the second half of this century. Furthermore, solar technologies could improve the lives of hundreds of millions of people currently lacking access to electricity.

The following chapters (4 and 5) consider how various forms of solar energy (electricity, heat and fuels) can be combined to match the needs of the large energy consuming sectors (buildings, industry and transportation).

Part B. Solar technologies

The next four chapters will more precisely assess the state of the art of solar energy technologies, possible improvements and research, development and demonstration needs. Photovoltaics come first in Chapter 6, followed by solar heat in Chapter 7. As they derive from collecting solar energy as heat, analyses of solar thermal electricity and solar fuels follow in Chapters 8 and 9.

Part C. The way forward

Chapter 10 elaborates on the costs of the incentive systems, and how they distinguish themselves from the bulk of investment costs in solar energy technologies. It then investigates the advantages and possible downsides of the various support schemes.

Chapter 11 looks farther into the future, considering whether a global economy entirely based on solar and other renewable energy resources is possible – and what are the likely limits.

A brief conclusion summarises the results and defines areas for future work.

PART A
MARKETS AND OUTLOOK

Chapter 2
The solar resource and its possible uses

The solar resource is enormous compared to our energy needs. It can be captured and transformed into heat or electricity. It varies in quantity and quality in places but also in time, in ways that are not entirely predictable. Its main components are direct and diffuse irradiance. The resource is not as well known as one may think – some knowledge gaps have still to be filled.

The incoming solar radiation

Each second, the sun turns more than four million tonnes of its own mass – mostly hydrogen and helium – into energy, producing neutrinos and solar radiation, radiated in all directions. A tiny fraction – half a trillionth – of this energy falls on Earth after a journey of about 150 million kilometres, which takes a little more than eight minutes.

The solar irradiance, *i.e.* amount of power that the sun deposits per unit area that is directly exposed to sunlight and perpendicular to it, is 1 368 watts per square metre (W/m^2) at that distance. This measure is called the solar constant. However, sunlight on the surface of our planet is attenuated by the earth's atmosphere so less power arrives at the surface — about 1 000 W/m^2 in clear conditions when the sun is near the zenith.

Our planet is not a disk, however, but a kind of rotating ball. The surface area of a globe is four times the surface area of a same-diameter disk. As a consequence, the incoming energy received from the sun, averaged over the year and over the surface area of the globe, is one fourth of 1 368 W/m^2, *i.e.* 342 W/m^2.

Of these 342 W/m^2 roughly 77 W/m^2 are reflected back to space by clouds, aerosols and the atmosphere, and 67 W/m^2 are absorbed by the atmosphere (IPCC, 2001). The remaining 198 W/m^2, *i.e.* about 57% of the total, hits the earth's surface (on average).

The solar radiation reaching the earth's surface has two components: direct or "beam" radiation, which comes directly from the sun's disk; and diffuse radiation, which comes indirectly. Direct radiation creates shadows, diffuse does not. Direct radiation is casually experienced as "sunshine", a combination of bright light and radiant heat. Diffuse irradiance is experienced as "daylight". On any solar device one may also account for a third component – the diffuse radiation reflected by ground surfaces. The term global solar radiation refers to the sum of the direct and diffuse components.

In total, the sun offers a considerable amount of power: about 885 million terawatthours (TWh) reach the earth's surface in a year, that is 6 200 times the commercial primary energy consumed by humankind in 2008 – and 4 200 times the energy that mankind would consume in 2035 following the IEA's Current Policies Scenario.[1] In other words, it takes the

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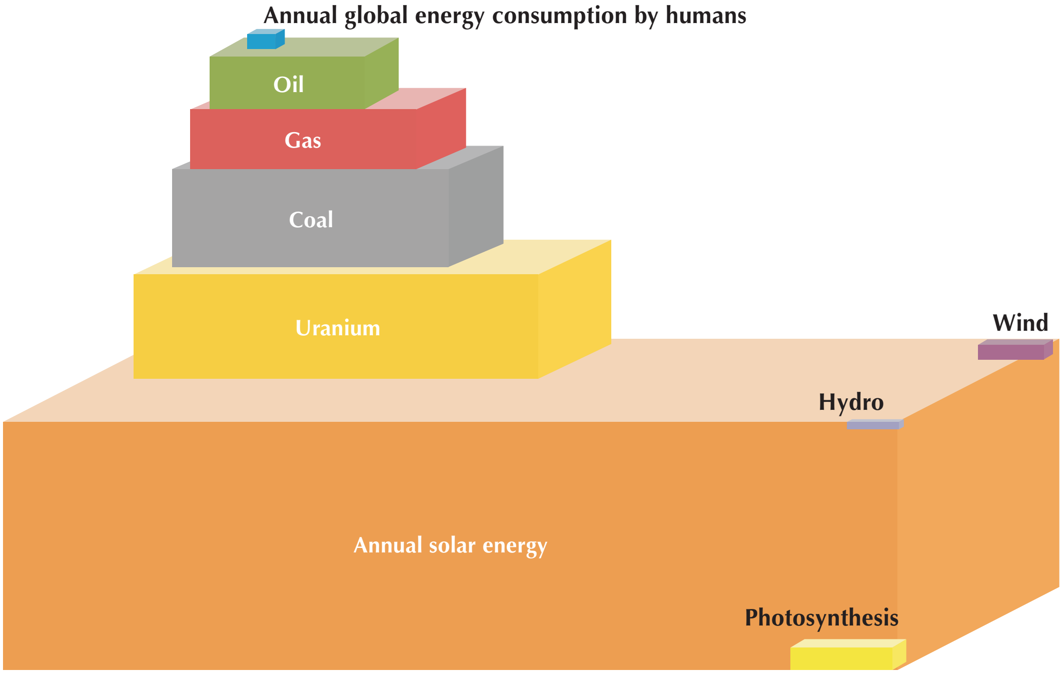
[1] *Global primary energy supply in 2008 was 142 712 TWh. In the current policy scenario, by 2035 this number would climb to 209 900 TWh. Global final energy consumption was 97 960 TWh in 2008 and would be 142 340 TWh by 2035 in the current policy scenario (IEA, 2010*b*). *The difference between primary energy supply and final energy consumption represents the losses in the energy system, notably in fossil-fuelled electric plants, and in the traditional uses of biomass.*

sun one hour and 25 minutes to send us the amount of energy we currently consume in a year, or a little more than 4.5 hours to send the same amount of energy only on land. By 2035, according to the scenario, these numbers would grow to a little more than two hours and a little less than seven hours, respectively. A comparison focused on final energy demand (see footnote) would significantly reduce these numbers – to one hour of sunshine on the whole planet or 3.25 hours on land today, and by 2035 1.5 hour or 4.75 hours.

While proven fossil reserves represent 46 years (oil), 58 years (natural gas) and almost 150 years (coal) of consumption at current rates (IEA, 2010*b*), the energy received by the sun in one single year, if entirely captured and stored, would represent more than 6 000 years of total energy consumption. Capture and distribute one tenth of one percent of solar energy, and the energy supply problem disappears.

The annual amount of energy received from the sun far surpasses the total estimated fossil resources, including uranium fission (Figure 2.1). It also dwarfs the yearly potential of renewable energy deriving from solar energy: photosynthesis (*i.e.* biomass), hydro power and wind power. The important element missing is geothermal energy, which is the large renewable energy resource that does not derive from solar energy. Its theoretical potential is immense, but likely to be much harder to tap on a very large scale than solar energy.[2]

Figure 2.1 **Total energy resources**



Source: National Petroleum Council, 2007, after Craig, Cunningham and Saigo (republished from IEA, 2008b).

Key point

Solar energy is the largest energy resource on Earth – and is inexhaustible.

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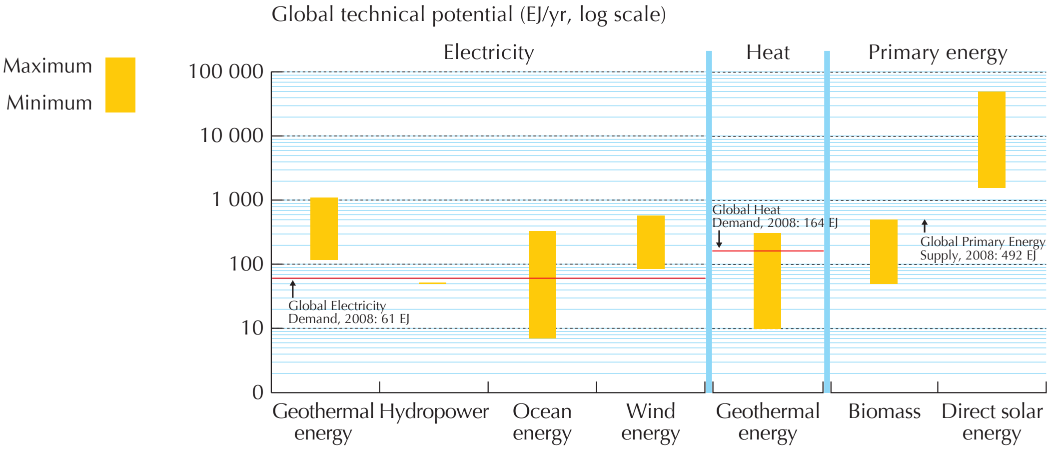
[2] *The heat trapped under the earth's surface is enormous, but the flux that comes naturally to the surface is very small on average compared to the solar energy on the same surface. (See IEA, 2011*b*).*

A recent special report on renewable energy published by the Intergovernmental Panel on Climate Change (IPCC, 2011) provides estimates of the global technical potential of renewable energy sources from a wide number of studies (Figure 2.2). They are shown on a logarithmic scale, due to the wide range of assessed data. Biomass and direct solar energy are shown as primary energy due to their multiple uses. Interestingly, the lowest estimate of the technical potential for direct solar energy is not only greater than the current global primary energy supply; it is also greater than the highest estimate of any other renewable energy potential.

Figure 2.2 **Global technical potentials of energy sources**



Notes: Biomass and solar are shown as primary energy due to their multiple uses; the figure is presented in logarithmic scale due to the wide range of assessed data. Technical potentials reported here represent total worldwide potentials for annual RE supply and do not deduct any potential that is already being utilised. 1 exajoule (EJ) ≈ 278 terawatt hours (TWh).

Source: IPCC, 2011.

Key point

Solar energy potential by far exceeds those of other renewables.

Since routine measurements of irradiance began in the 1950s, scientists have observed a 4% reduction of irradiance. This was named "global dimming" and attributed to man-made emissions of aerosols, notably sulphate aerosols, and possibly also aircraft contrails. Global dimming may have partially masked the global warming due to the atmospheric accumulation of greenhouse gas resulting from man-made emissions. It could be responsible for localised cooling of regions, such as the eastern United States, that are downwind of major sources of air pollution. Since 1990 global dimming has stopped and even reversed into a "global brightening". This switch took place just as global aerosol emissions started to decline. In sum, neither dimming nor brightening should significantly affect the prospects of solar energy.

Other variations in solar irradiance are even less relevant for energy purposes. Short-term changes, such as those linked to the 11-year sunspot cycle, are too small (about 0.1% or 1.3 W/m^2). Larger foreseeable evolutions linked to astronomical cycles are too slow (in the scale of millennia). On a local scale, however, weather pattern variations between years are much more significant. Climate change due to increase of greenhouse gases in the atmosphere may influence cloud cover and reduce clarity, and the potential of the solar energy resource in different regions of the globe. Current models suggest, however, that monthly average changes in solar fluxes will remain very low – though this is not necessarily true with respect to direct normal irradiance.

Two basic ways to capture the sun's energy

Solar rays can be distinguished according to their wavelengths, which determine visible light, infrared and ultraviolet radiation. Visible light constitutes about 40% of the radiated energy, infrared 50% and ultraviolet the remaining 10%. Most of the infrareds are "near infrared" or "short-wave infrared" rays, with wavelengths shorter than 3 000 nanometres, so they are not considered "thermal radiation".

The sun's primary benefit for most people is light, the use of which can be improved in buildings to reduce energy consumption. This area of development, called day lighting, is one of the avenues to reducing energy consumption in buildings.

Solar irradiative energy is easily transformed into heat through absorption by gaseous, liquid or solid materials. Heat can then be used for comfort, in sanitary water heating or pool water heating, for evaporating water and drying things (notably crops and food), and in space heating, which is a major driver of energy consumption. Heat can also be transformed into mechanical work or electricity, and it can run or facilitate chemical or physical transformations and thus industrial processes or the manufacture of various energy vectors or fuels, notably hydrogen.

However, solar radiation can also be viewed as a flux of electromagnetic particles or photons. Photons from the sun are highly energetic, and can promote photoreactions such as in photosynthesis and generate conduction of electrons in semiconductors, enabling the photovoltaic conversion of sunlight into electricity. Other photoreactions are also being used, for example photocatalytic water detoxification.

Note that the two fundamental methods to capture energy from the sun – heat and photoreaction – can also be combined in several ways to deliver combined energy vectors – *e.g.* heat and electricity.

Thus, from the two basic ways of capturing the sun's energy, apart from day lighting, *i.e.* heat and photoreaction, we distinguish four main domains of applications: photovoltaic electricity, heating (and cooling), solar thermal electricity, and solar fuel manufacture. The relevant technologies are detailed in Chapters 6 to 9 of this publication.

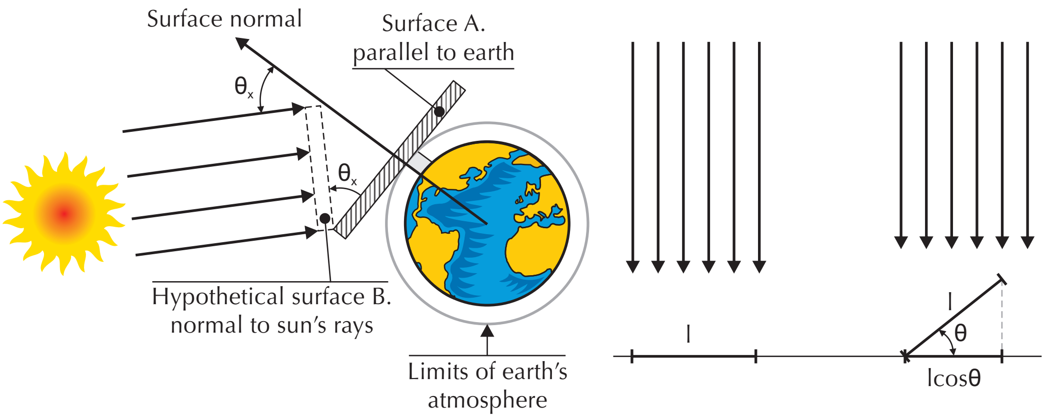
How this resource varies

Although considerable, the solar resource is not constant. It varies throughout the day and year, and by location. For a large part, these variations result directly from the earth's geography and its astronomical movements (its rotation towards the East, and its orbiting the sun). But these variations are accentuated and made somewhat less foreseeable from day to day by the interplay between geography, ocean and land masses, and the ever-changing composition of the atmosphere, starting with cloud formation.

All places on earth have the same 4 380 hours of daylight hours per (non-leap) year, *i.e.* half the total duration of a year. However, they receive varying yearly average amounts of energy from the sun. The earth's axis of rotation is tilted 23.45° with respect to the ecliptic – the plane containing the orbit of the earth around the sun. The tilting is the driver of seasons. It results in longer days, and the sun being higher in the sky, from the March equinox to the September equinox in the northern hemisphere, and from the September equinox to the March equinox in the southern hemisphere.

When the sun is lower in the sky, its energy is spread over a larger area, and is therefore weaker per surface area. This is called the "cosine effect". More specifically, supposing no atmosphere, in any place on a horizontal surface the direction of the sun at its zenith forms an angle with the vertical. The irradiance received on that surface is equal to the irradiance on a surface perpendicular to the direction of the sun, multiplied by the cosine of this angle (Figure 2.3).

Figure 2.3 **The cosine effect**



Note: As a plate exposed to the sun tilts, the energy it receives varies according to the cosine of the tilt angle.

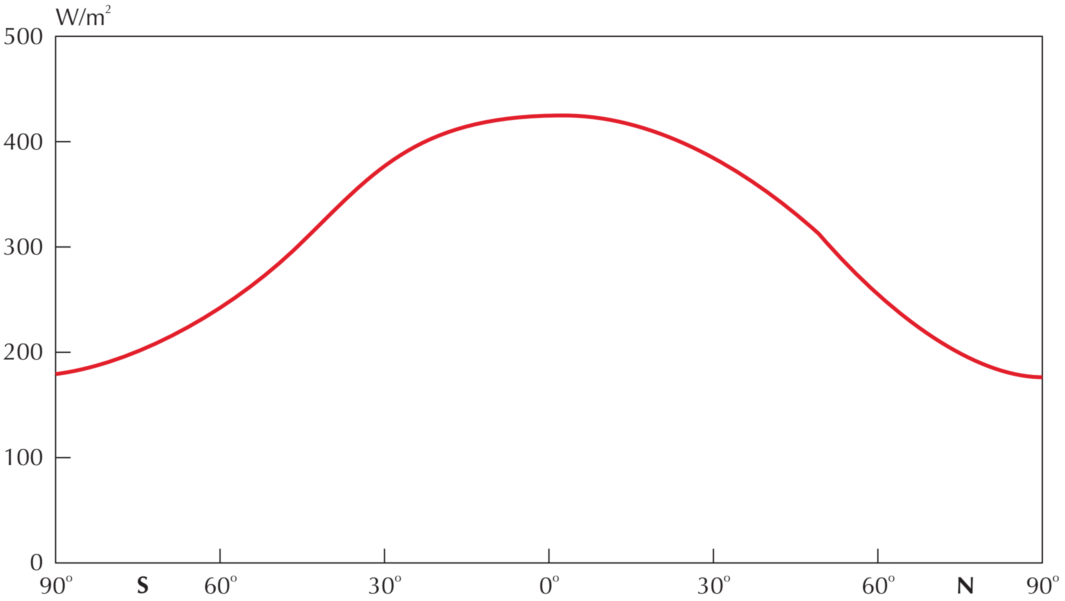
Source: Stine and Geyer, 2011(left).

Key point

Solar irradiance is maximal when the sun is directly overhead.

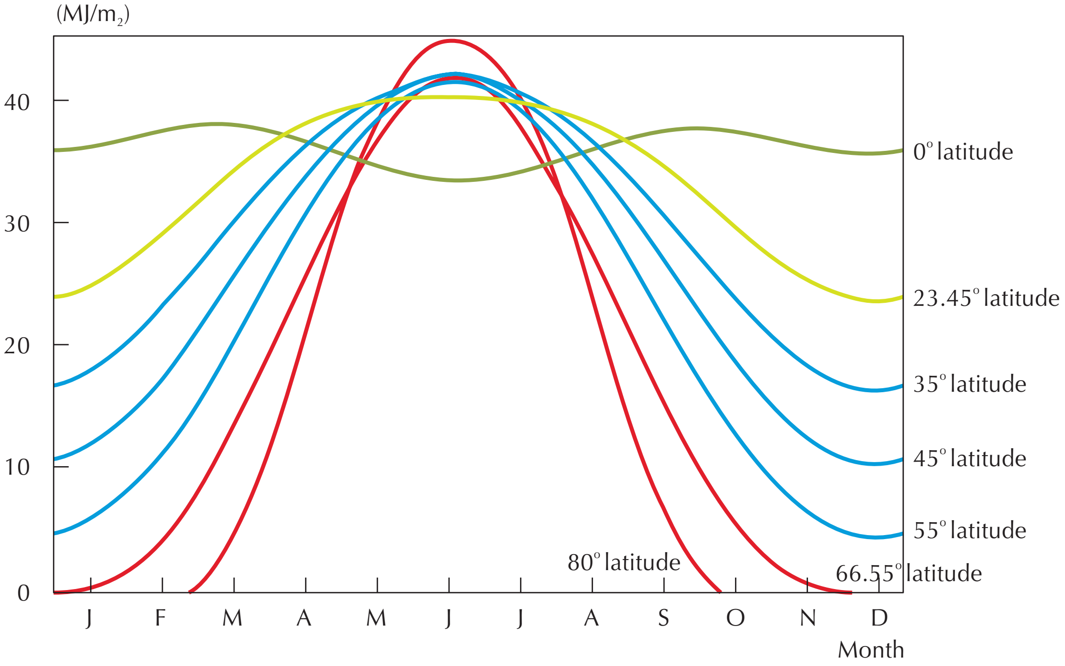
Tilting also leads to definition of two imaginary lines that delineate all the areas on the earth where the sun reaches a point directly overhead at least once during the solar year. These are the tropics, situated at 23.45° latitude on either side of the equator. Tropical zones thus receive more radiation per surface area on yearly average than the places that are north of the Tropic of Cancer or south of the Tropic of Capricorn. Independent of atmospheric absorption, the amount of available irradiance thus declines, especially in winter, as latitudes increase. The average extraterrestrial irradiance on a horizontal plane depends on the latitude (Figure 2.4). Irradiance varies over the year at diverse latitudes – very much at high latitudes, especially beyond the polar circles, and very little in the tropics (Figure 2.5).

Figure 2.4 **Average yearly irradiance**



Source: unless otherwise indicated all material in figures and tables drivers from IEA data and analysis.

Figure 2.5 **Total daily amount of extraterrestrial irradiance on a plane horizontal to the earth surface**



Source: Itacanet.

Key point

Seasonal variations are greater at higher latitudes.

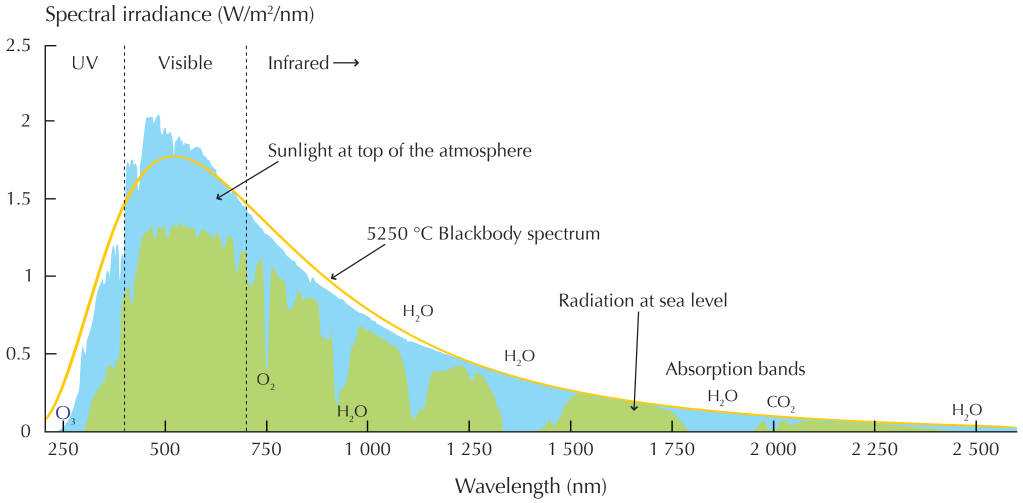
Figure 2.5 shows that there are days where the polar regions receive higher irradiance than all other places on earth, with about 13.5 kWh/m^2/day at the December solstice for the South Pole and 12.6 kWh/m^2/day at the June solstice for the North Pole, *versus* about 10 kWh/m^2/day at the equator. This gap is probably accentuated, not diminished, by differences in the transparency of the atmosphere in both places. Poles are the sunniest places on earth, but only for a few days per year because summer days within the polar circles last 24 hours, against only 12 hours at the equator.[3]

However, this basic model is complicated by the atmosphere, and its content in water vapour and particles, which also vary over time and place. Clouds bar almost all direct beam radiation. The composition of the atmosphere has two main implications for availability of the solar energy.

First, the cosine effect is compounded by the greater distance the sun's rays must travel through the earth's atmosphere to reach the earth's surface when the apparent sun is lower in the sky – twice as much when the sun's direction forms a 60° angle with the direction of the zenith. This is termed an "air mass" value of 2, *versus* a value of 1 when the sun is exactly overhead.

Second, the atmosphere scatters and absorbs some of the solar energy – particularly infrared radiation absorbed by the water vapour and CO_2 trace gases of the atmosphere, and ultraviolet radiations absorbed by ozone. Visible light, near and short-wave infrareds, being the more energetic types of solar radiation (the shorter the wavelength, the higher the energy), comprise more than 95% of the solar radiation at sea level (Figure 2.6).

Figure 2.6 **Solar radiation spectrum at the top of the atmosphere and at sea level**



Note: The solar radiation at the top of the atmosphere is in yellow, the radiation reaching the sea level is in red. The bulk of the energy is made of visible light and near infrared.

Key point

Visible light and near infra-red constitute the bulk of incident solar radiation.

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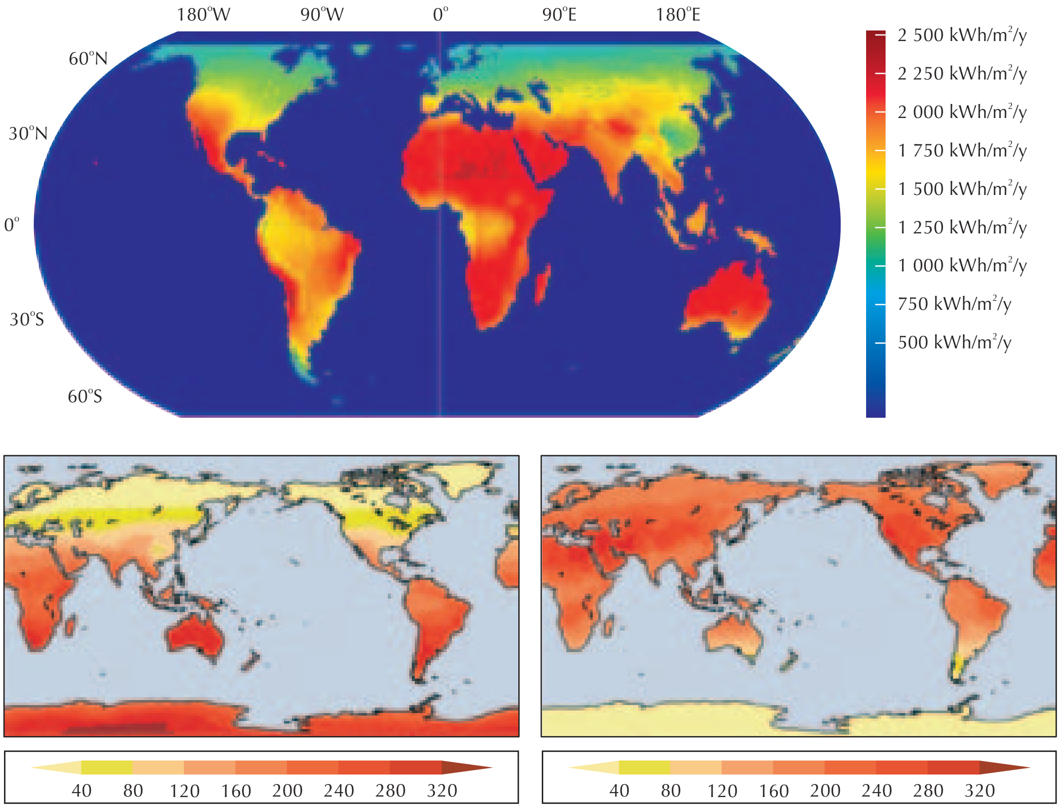
[3] *The South Pole is sunnier than the North Pole because the earth's orbit is an ellipse and the sun closer to us during the winter of the northern hemisphere. Thus, the so-called solar "constant" is in reality only about 1 320 W/m^2 on 2 July versus 1 415 W/m^2 on 2 January.*

Roughly half of the radiation scattered is lost to outer space, the remainder is directed towards the earth's surface from all directions (diffuse radiation). The amount of energy reflected, scattered and absorbed depends on the length the sun's rays must travel, as well as the levels of dust particles and water vapour – and of course the clouds – they meet. Smaller cosine effect and air mass make the inter-tropical zone sunnier than others. However, the global radiation reaching the earth's surface is much stronger in arid or semi-arid zones than in tropical or equatorial humid zones (Figure 2.7). These zones are usually found on the west sides of the continents around the tropics, but not close to the equator.

Figure 2.7 **The global solar flux (in kWh/m²/y) at the Earth's surface over the year (top), winter and summer (bottom)**



December, January, February

June, July, August

Sources: (top) Breyer and Schmidt, 2010a; (bottom) ISCCP Data Products, 2006/IPCC, 2011.

Key point

Global solar irradiance is good to excellent between 45° South and 45° North.

The average energy received in Europe is about 1 200 kWh/m² per year. This compares, for example, with 1 800 kWh/m² to 2 300 kWh/m² per year in the Middle East. The United States, Africa, most of Latin America, Australia, most of India and parts of China also have good-to-excellent solar resource. Alaska, northern Europe, Canada, Russia and South-East China are somewhat less favoured. It happens that the most favoured regions are broadly those where much of the increase in energy demand is expected to take place in the coming decades.

By separating the direct and diffuse radiations, it is clear that direct sunlight differs more than the global resource. There is more diffuse irradiance around the year in the humid tropics, but not more total energy than in southern Europe or Sahara deserts (Figure 2.8).

Arid areas also exhibit less variability in solar radiation than temperate areas. Day-to-day weather patterns change, in a way that meteorologists are now able to predict with some accuracy. The solar resource also varies, beyond the predictable seasonal changes, from year to year, for global irradiance and even more for direct normal irradiance. Figure 2.9 illustrates this large variability in showing the global horizontal irradiance (GHI) in Potsdam, Germany (top), and deviations of moving averages across 1 to 22 years (bottom). One clear message is that a solar device can experience large deviations in input from one year to another. Another is that a ten-year measurement is needed to get a precise idea of the average resource. This is not measurement error – only natural variability.

Tilting collectors, tracking and concentration

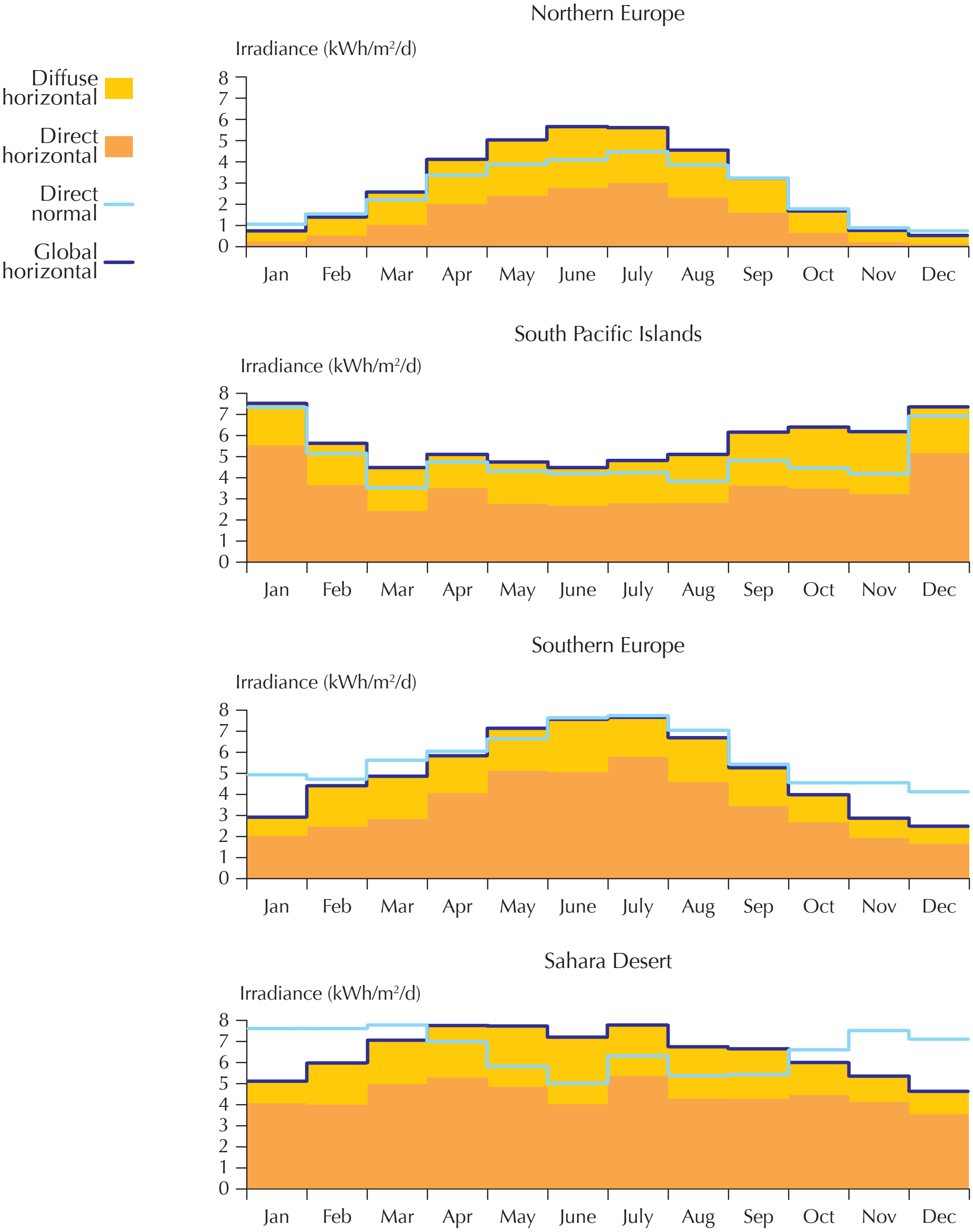
Global irradiance on horizontal surfaces (or global horizontal irradiance [GHI]) is the measure of the density of the available solar resource per surface area, but various other measures of the resource also need to be taken into account. Global irradiance could also be defined on "optimum" tilt angle for collectors, *i.e.* for a receiving surface oriented towards the Equator tilted to maximise the received energy over the year.

Tilting collectors increases the irradiance (per receiver surface area) up to 35% or about 500 kWh/m^2/y, especially for latitudes lower than 30°S and higher than 30°N (Figure 2.10). The optimal tilt angle is usually considered to be equal to the latitude of the location, so the receiving surface is perpendicular to the sun's rays on average within a year. However, when diffuse radiation is important, notably in northern Europe and extreme southern Latin America, the actual tilt angle maximising irradiance can be up to 15° lower than latitude. The economically optimal tilt angle can differ from the irradiance optimised tilt angle, depending on the type of application and the impact of tilt angles on the overall investment cost.

Other potentially useful measures include the global irradiance for one-axis tracking surface and the global irradiance for two-axis tracking surface. This defines the global normal irradiance (GNI), which is the maximum solar resource that can be used. Direct irradiance is more often looked at under the form of direct normal irradiance (DNI) – the direct beam irradiance received on a surface perpendicular to the sun's rays.

The respective proportions of direct and diffuse irradiance are of primary importance for collecting the energy from the sun and have many practical implications. Non-concentrating technologies take advantage of the global radiation, direct and diffuse (including the reflections from the ground or other surfaces) and do not require tracking. If sun-tracking is used with non-concentrating solar devices, it need not be very precise and therefore costly, while it increases the amount of collected solar energy. It allows taking advantage of the best possible resource. This is worthwhile in some cases, but not that many, as expanding a fixed receiver area is often a less costly solution for collecting as much energy.

Figure 2.8 **The yearly profile of mean daily solar radiation for different locations around the world**



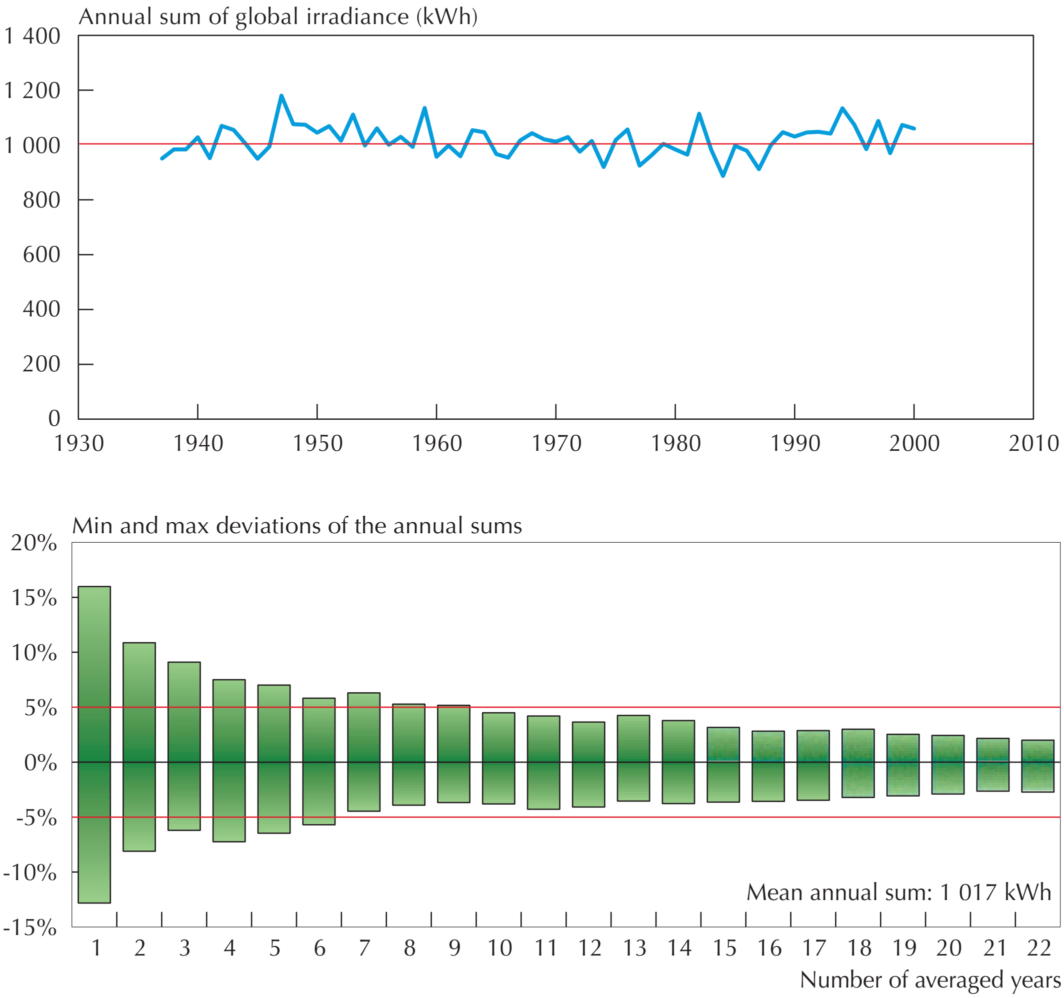
Note: The dark area represents direct horizontal irradiance, the light area diffuse horizontal irradiance. Their sum, global horizontal irradiance (GHI) is the black line. The blue line represents direct normal irradiance (DNI).

Source: Chhatbar & Meyer, 2011.

Key point

Temperate and humid equatorial regions have more diffuse than direct solar radiation.

Figure 2.9 **Global horizontal irradiance (GHI) in Potsdam (Germany) and moving averages**



Note: The bottom figure shows the deviations from long-term average GHI of the moving averages across 1 to 22 years.

Sources: Datasource: DWD GHI Data from 1937 to 2003 (top); Volker Quaschning, DLR/Hoyer-Klick et al. *2010 (bottom).*

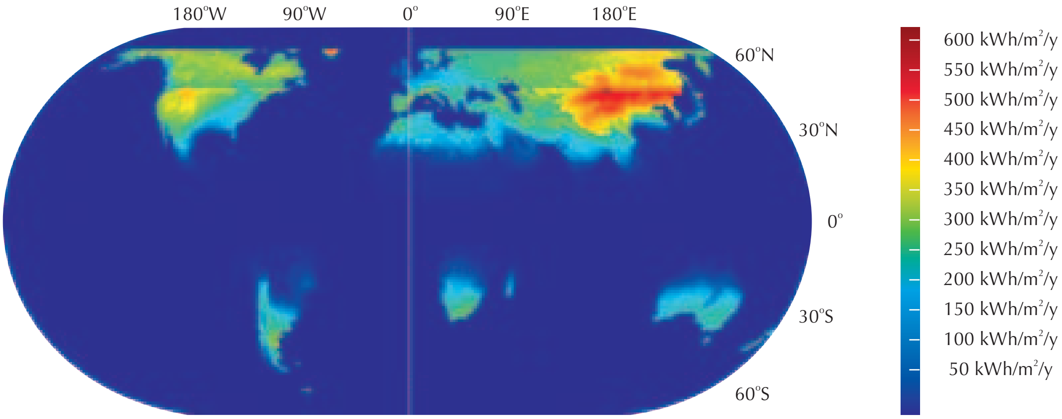
Key point

Solar energy resource varies from year to year, as well as day to day.

Where DNI is important, one may want to concentrate the sun's rays, usually by reflection from a large area to a smaller one. The main reason for doing this could be to increase the energy flux per collector surface area and thus efficiencies in collecting and converting the sun's energy. It thus opens up a broader range of possibilities, as shown in Part B. Another reason could be to substitute large expensive collector areas with a combination of less costly reflective areas and expensive but smaller "receiving" areas.

Concentrating the sun's rays on a receiver requires reflective surface(s) to track the diurnal (daily) movement of the apparent sun in the sky, to keep the receiver in the focus of reflector(s). The concentration factor, *i.e.* the ratio of the reflector area to the receiver area, is casually measured in "suns": ten "suns" means a concentration of a factor ten.

Figure 2.10 **Increase in collected energy on optimally titled collectors *versus* horizontal ones**



Note: The map shows the increase in collected energy gained by tilting the receiving surfaces at its optimal angle.

*Source: Breyer and Schmidt, 2010*a.

Key point

Collector tilt angle reduces geographical disparities in available solar energy resource.

But tracking the sun comes at a cost. Higher concentration factors require more precise tracking, which entail higher costs. Furthermore, the diffuse radiation incoming onto the reflector does not hit the receiver and is lost. The importance of this loss is shown in juxtaposing global normal and direct normal irradiance levels worldwide (except the Poles) (Figure 2.11).

In any case, concentrating technologies can be deployed only where DNI largely dominates the solar radiation mix, *i.e.* in sunny countries where the skies are clear most of the time, over hot and arid or semi-arid regions of the globe. These are the ideal places for concentrating solar power (CSP), concentrating photovoltaics (CPV), but also manufacturing of solar fuels and, of course, other industrial uses of high-temperature solar heat. These are also regions where solar desalination is likely to take place, given the usual scarcity of water.

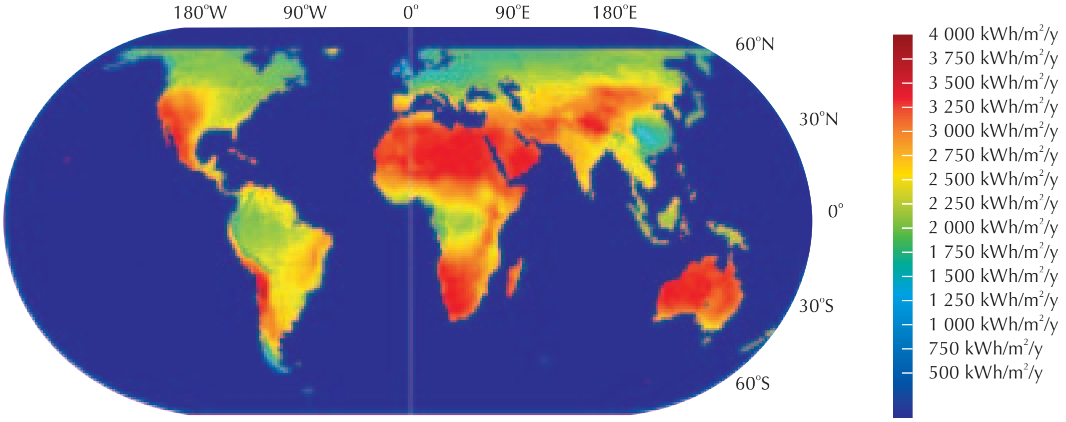
In humid equatorial regions, sunshine is abundant but the diffuse component is relatively more important so concentrating technology is less suitable. PV would work fine, but so do solar water heaters and some other uses of solar heat, from crop drying to process heat, and some forms of solar cooking.

It is often beyond 40° of latitude (north or south) or at high altitudes that solar space heating is most profitable. Indeed, the same phenomenon that makes the air cooler at altitude (*i.e.* the lower density of the atmosphere) also makes the sunshine stronger, when the weather is fine. Here, land relief is important, as it heavily influences the availability of sunshine.

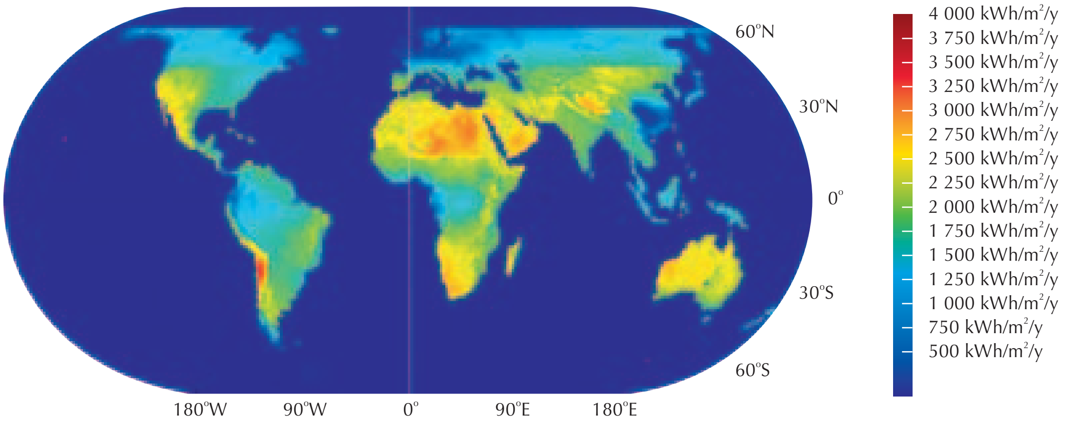
Concentrating PV has only a small share in the current PV market, and a very large majority of the market for solar heat today is based on non-concentrating collectors. Concentrating solar power takes all the current market for solar thermal electricity, and is the only available technology option for manufacturing solar fuels.

Figure 2.11 **Global normal (top) and direct normal (bottom) Irradiance**

Global normal irradiance (GNI)



Direct normal irradiance (DNI)



Notes: Global normal irradiance offers the maximum resource and requires two-axis sun-tracking (top). Two-axis sun-tracking with concentration devices leads to direct normal irradiance (bottom), losing the diffuse component.

*Source: Breyer and Schmidt, 2010*b.

Key point

Tracking increases the collected energy; concentration narrows it to direct light.

Knowing the resource is key to its exploitation

As the solar resource varies in large proportion with location and time-scales, a solar project of any kind requires a good amount of knowledge on the actual resource. This requires assessing not only the overall global solar energy available, but also the relative magnitude of its three components: direct-beam irradiance, diffuse irradiance from the sky including clouds, and irradiance by reflection from the ground surface. Also important are the patterns of seasonal availability, variability of irradiance, and daytime temperature on site. As seen above, long-term measurement is necessary to avoid being misled by the annual variability, especially in temperate regions.

The World Radiation Data Centre (WRDC) was established by the World Meteorological Organisation in 1964 and is located at the Main Geophysical Observatory in St. Petersburg, Russia. It serves as a central depository for solar radiation data collected at over 1 000 measurement sites throughout the world (see Box: Measuring the solar resource from the ground). By centrally collecting, archiving and publishing radiometric data from the world, the centre ensures the availability of these data for research by the international scientific community.

The WRDC archive contains the following measurements for most sites: global solar radiation, diffuse solar radiation, and "sunshine duration", defined as the sum of the periods during which the direct solar irradiance exceeds 120 W/m^2 – *i.e.* when the solar disk is visible and shadows appear behind illuminated objects.

Formulations such as "a daily average of 5.5 hours of sunshine over the year" are casually used, however, to mean an average irradiance of 5.5 kWh/m^2/d (2 000 kWh/m^2/y), *i.e.* the energy that would have been received had the sun shone on average for 5.5 hours per day with an irradiance of 1 000 W/m^2. In this case, one should preferably use "peak sunshine" or "peak sun hours" to avoid any confusion with the concept of sunshine duration.

Measuring the solar resource from the ground

The primary instrument used to measure global solar irradiance is the pyranometer, which measures the sun's energy coming from all directions in the hemisphere above the plane of the instrument.

An instrument called a normal incidence pyrheliometer or NIP is used to measure the direct normal component of the solar irradiance. This device is essentially a thermopile pyranometer placed at the end of a long tube aimed at the sun. The aspect ratio of the tube is usually designed to accept radiation from a cone of about 5°. A two-axis tracking mechanism maintains the sun's disc within the acceptance cone of the instrument.

Pyranometers may be modified to measure only the diffuse component of the global horizontal radiation. Providing a "shadowing" device just large enough to block out the direct irradiance coming from the sun's disc does this. Incorporating a shadow band avoids moving a shadowing disc throughout the day. This band must be adjusted often during the year to keep it in the ecliptic plane. Since the shadow band blocks part of the sky, corrections for this blockage are needed.

Recently, rotating shadow band pyranometers have come into general use. With this design, the shadow band rotates slowly about the pyranometer, blocking the direct irradiance from the sun every time it passes in front of the pyranometer. The signal from the pyranometer reads GHI most of the time, with reductions down to the diffuse irradiance level when the shadow band passes between the sun and the pyranometer. This design gives the advantage of using a single pyranometer to measure both global horizontal and diffuse horizontal solar irradiance. The rotating shadow band pyranometer is used to determine the direct normal irradiance without using a pyrheliometer, by measuring the difference between global and diffuse horizontal irradiances and the sun's elevation angle.

A traditional measurement is also often reported in meteorological observations. This is the "duration of sunshine." The standard instrument used to measure this parameter is the Campbell-Stokes sunshine recorder, which consists of a glass sphere that focuses the direct solar radiation and burns a trace on a special pasteboard card. These recorders have been replaced in most installations by photo detector activated "sunshine switches". The data produced by these instruments are of minimal use to engineers because there is no measure of intensity other than threshold intensity. However, attempts have been made to correlate these data with daily or monthly solar radiation levels.

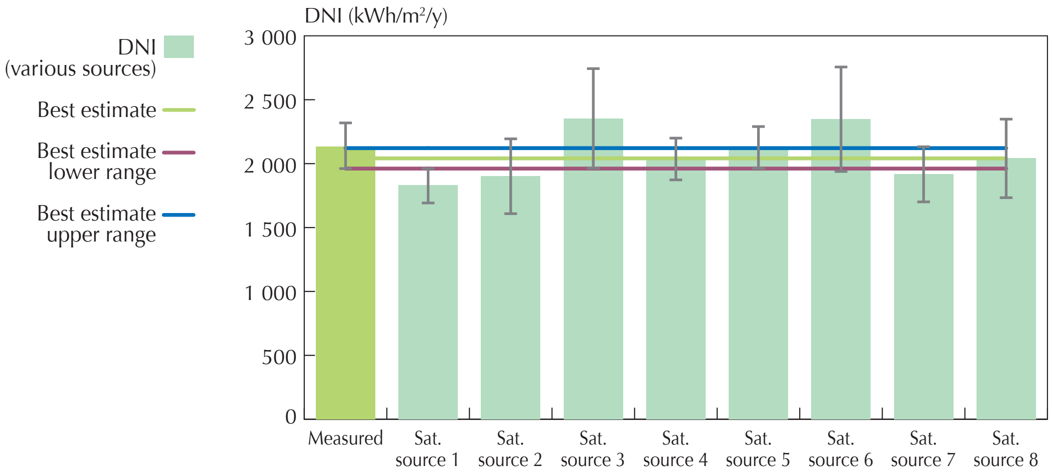
Periodic ground observations of cloud cover also provide useful information. These are made at least hourly at weather observation stations around the world. Cloud-cover data along with other weather data have been used to predict solar irradiance levels for locations without solar irradiance measurement capabilities.

Meteorological satellites in space can help fill in the resource knowledge gaps. The considerable advantage they offer is a complete coverage of the inhabited regions of the world, as well as the time depth for those that have been in service for years. Ground stations are scarce and cannot rival the resolution of satellites, often of 10-km scale. Interpolations can be simply wrong as weather patterns change on relatively small scales.

However, the information delivered by satellites is not reliable enough, especially with respect to DNI, which is the relevant information for any concentrating system. Existing geographic information systems focused on solar and other renewable data show differences in estimates. For example, eight satellite data sets from different providers for one specific location in Spain were analysed and compared to ground measurements. DNI values ranged from 1 800 kWh/m^2/y up to 2 400 kWh/m^2/y (Figure 2.12). Other examples, easily found, for example, on the Solar and Wind Energy Resource Assessment (SWERA) website, would reveal even larger differences. Similar tests on GHI data – the relevant information for non-concentrating devices – would show significantly smaller discrepancies.

Therefore, in many cases ground measurements are critically necessary for a reliable assessment of the solar energy possibilities of sites, especially if the technology envisioned depends on concentrating the sun's rays. Nevertheless, satellite data can be used in this case to complement short ground measurement periods of one or two years with a longer term perspective. Ten years is the minimum necessary to have a real perspective on annual variability, and to get a sense of the actual average potential and the possible natural deviations from year to year. Satellite data should be used only when they have been benchmarked by ground measurements, at least as far as DNI and concentrating devices are concerned.

Figure 2.12 **Comparison of satellite data sources with best estimate from on-ground measurement**



Source: Meyer, 2011.

Key point

Satellite data must be confirmed by ground measurements, especially for DNI.

Chapter 3
Solar electricity

Generating carbon-free electricity will not only eliminate the current carbon dioxide emissions from electricity generation, but also help eliminate emissions resulting from direct fossil fuel consumption in the building, industry and transport sectors through increased electrification. PV is developing rapidly and its costs are falling just as fast. Solar thermal electricity (STE) lags behind but, thanks to heat storage, offers considerable potential. As their accessible markets expand, these technologies look more complementary than competitors.

Background

Terrestrial applications of solar photovoltaics (PV) began in the 1970s, and developed in niche off-grid applications, mostly rural electrification and telecommunications. In the 1980s, the first commercial concentrating solar power (CSP) plants generating STE (backed by 25% natural gas) were built in California's Mohave Desert, and were based on federal and state tax incentives for investors and mandated long-term power purchase agreements. They totalled 354 MWe by 1991 when Luz, the builder, filed for bankruptcy. They are still operating today.

In the 1990s, various countries introduced incentives to support early deployment of solar photovoltaic systems. In 1995, the Japanese 70 000 solar roofs programme began, initially providing 50% subsidy of the cost of installed grid-tied PV systems. The German 100 000 solar roofs programme began in 1999, followed by the Renewable Energy law in 2000, which offered a EUR 0.5/kWh feed-in tariff on installed systems for 20 years. In 1998, Japan surpassed the United States as the leading market. Germany took the second position in 2001, and overtook Japan in 2003. It has since remained the market leader.

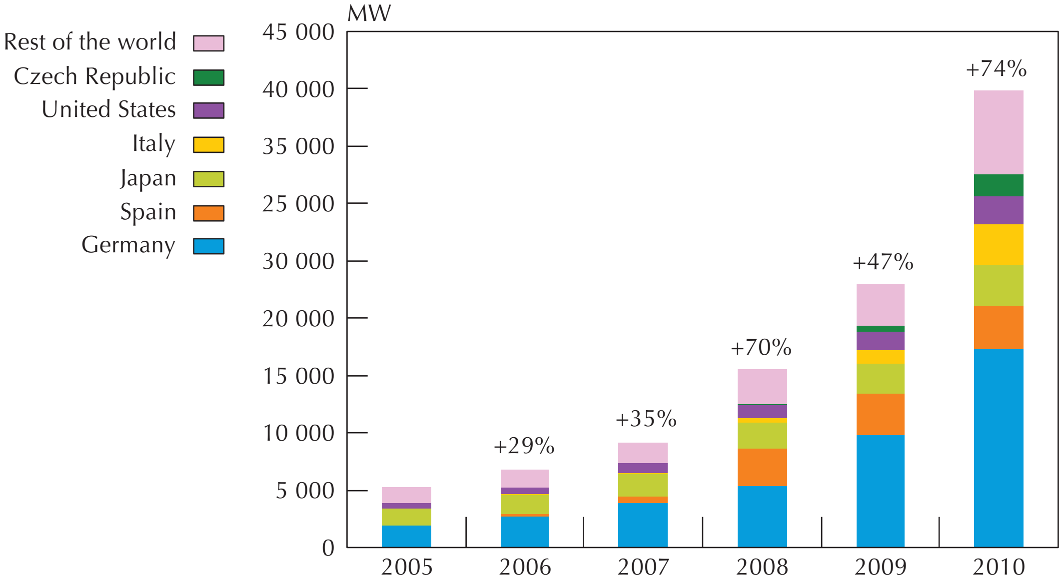
The growth of the global PV market has been impressive since 2003, with an average annual growth rate of 40% to 2009, and about 135% in 2010. The cumulative installed global PV capacity grew from 0.1 GW in 1992 to 40 GW at the end of 2010, with 42% being installed in 2010 alone (Figure 3.1).

Meanwhile, a new wave of CSP plant building was initiated in 2005 in Spain and the United States, with smaller realisations in a few other countries (Algeria, Egypt, and Morocco). STE cumulative capacities neared 1 GW at the end of 2010 with several more GW under construction or in planning ever after 3 GW of CSP projects in the United States were turned into PV in 2011. The figure 3.2 presents CSP targets and plants (operational, under construction and planned) as of September 2011, after several CSP project were turned into PV project in the USA notably California.

The bright future for electricity

Electricity is more easily decarbonised than other fuels. It is thus set to play an ever-increasing role in a world struggling to reduce its energy-related carbon dioxide emissions, while enhancing energy security.

Figure 3.1 **Global cumulative PV capacities by 2010**

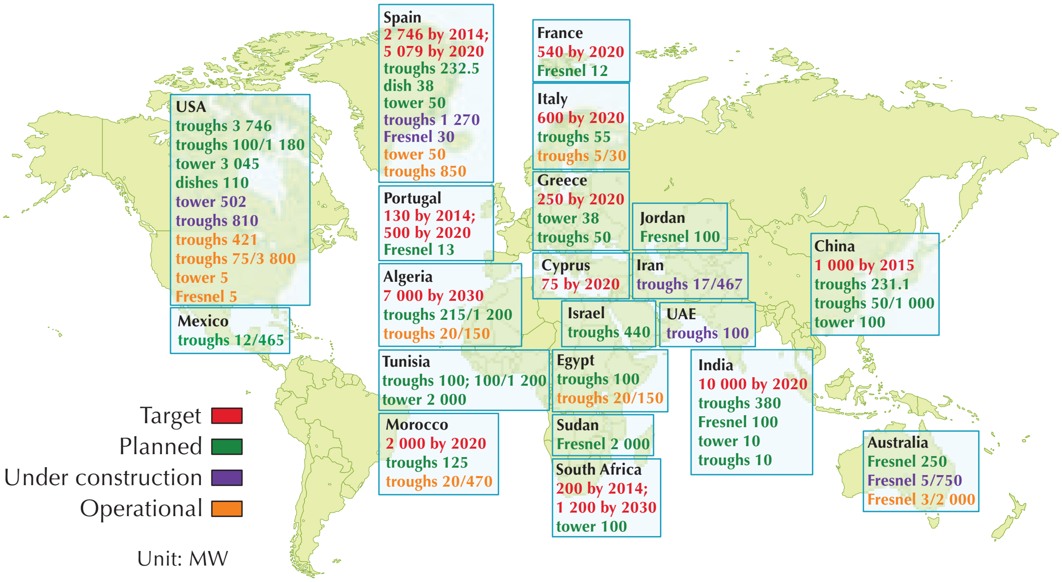


Sources: IEA PVPS, BP Statistical Report, BNEF.

Key point

Installed PV capacities show a steep growth curve.

Figure 3.2 **On-going CSP targets and plants (operational, under construction and planned)**



Note: xx/yy: for Integrated Solar Combined Cycle or fuel saver systems, xx indicates the solar capacity, yy indicates the overall capacity.

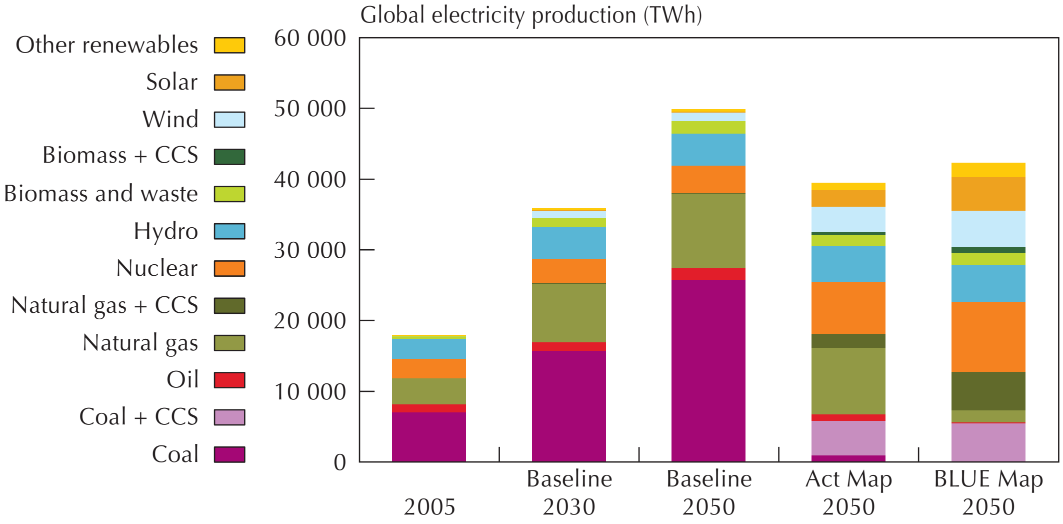
Key point

There are many more CSP plants under development than in production so far.

Versatile and clean electricity will thus continue to replace fossil fuels in buildings (notably through heat pumps), industry (via many applications) and transport, with a larger share of mass-transit systems and millions more electric vehicles (see Chapters 4 and 5). Demographic and economic growth and further electrification will combine to expand markets for renewable electricity in general, solar electricity in particular, including both photovoltaics (PV) and solar thermal electricity (STE) from concentrating solar power (CSP) plants. These two solar electricity technology families are presented in detail in Chapters 6 to 8.

The IEA publication, *ETP 2008*, offered the ACT Map Scenario, which would bring global energy-related CO_2 emissions back to 2005 levels by 2050 (IEA, 2008*b*). Comparing this scenario with the BLUE Map Scenario in the same publication, which would by 2050 bring emissions back to half the 2005 level, is instructive. Although a substantial part of the difference is explained by an increase in energy savings, more electricity is generated and consumed in the BLUE Map Scenario, as electricity replaces fossil fuel in buildings and transport (Figure 3.3).

Figure 3.3 **Global electricity production in 2050 under various scenarios**



*Source: IEA, 2008*b.

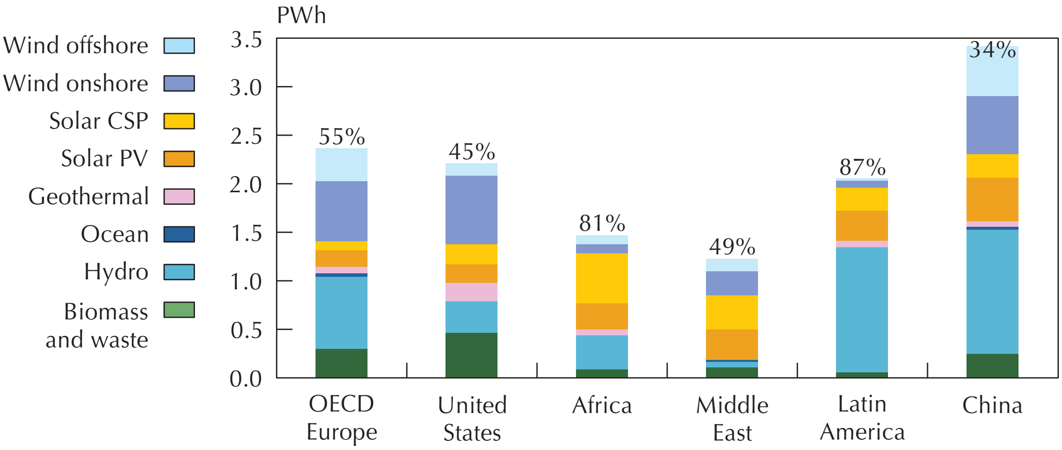
Key point

Clean electricity can replace many fossil fuel uses.

The BLUE Scenarios for solar electricity

As a result of deployment of a combination of STE/CSP and PV, solar electricity grows rapidly in all IEA scenarios – and more rapidly in climate-friendly scenarios. In the 450 Scenario of the *WEO 2010*, solar technologies generate 2 000 TWh/y of electricity worldwide by 2035. They would grow even faster thereafter, according to *ETP 2010*, reaching in the BLUE Map Scenario 4 958/y TWh by 2050. The renewable mix of regions/countries varies according to the various resources and the mix of solar electricity technology in line with the ratio of diffuse to direct irradiance (Figure 3.4).

Figure 3.4 **Renewables in electricity generation by 2050 in the Blue Map Scenario**



Source: IEA, 2010a.

Key point

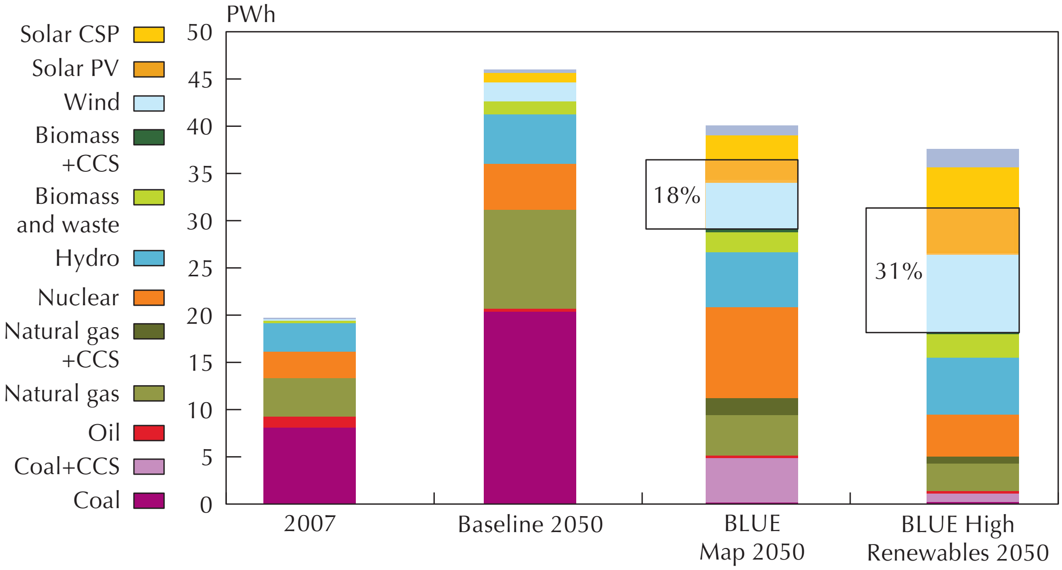
Available resources determine the mix of renewables in electricity generation.

More significantly perhaps, *ETP 2010* offers a BLUE Hi-Ren Scenario, where renewables are pushed up to 75% of global electricity generation. Such a scenario shows how renewables could replace other climate-change mitigation options that fail to deliver entirely on their promises – whether it be energy efficiency, CCS or nuclear power. In such a scenario, solar electricity will be, by 2050, the largest of all sources of electricity generation, accounting for almost 25% of the total. CSP and PV technologies contribute similar proportions to solar generation. Wind has the next largest share, followed by hydro.

Consistent with the BLUE Hi-Ren Scenario, the *IEA Roadmap: Solar Photovoltaic Energy* foresees PV producing about 11% of global electricity by 2050, including all scales and types of PV deployment (IEA, 2010*c*). The total PV capacity by 2050 would be 3 155 GW, of which 44% would be residential, 13% commercial (*i.e.* on large commercial buildings), 29% utility scale, and 14% off grid. As the latter two sectors are likely to be installed in sunnier places, they would total 48% of the global 4 572 TWh of PV-produced electricity, the residential sector providing only 39% of the total.

Solar energy, like wind power, varies by day, season, and year. Variable renewable generation (*i.e.* PV and wind power) would by 2050 provide between 18% and 31% of global electricity generation in the climate-friendly scenarios *BLUE Map* and *High Ren* of *ETP 2010* (see Figure 3.5).

Figure 3.5 **Share of variable renewables in global electricity generation by 2050**



Source: IEA, 2011c.

Key point

Variable renewables could represent one-third of total electricity generation by 2050.

Grids will need to evolve considerably to handle new tasks, such as managing more variable supply, sending appropriate and timely price signals to producers and customers, and managing demand loads. This is already seen in the evolution towards so-called **smart grids**. Increased interconnection between electric systems and countries will also help exploit all the benefits of the variable sources of electricity.

The challenges this variability raises in integrating renewable electricity sources should, however, not be overestimated, a recent IEA study suggests (see Box: Harnessing variable renewables). The capacity of electric grids to integrate variable renewables depend on their flexibility, *i.e.*: the capability of the power system as a whole to ramp electricity supply or demand up or down, in response to variability and uncertainty in either. The need for flexibility is not introduced by the deployment of variable renewables, as all electric systems already have flexibility to meet variable demand, and the contingencies that may affect all generating sources and transmission capacities. Flexibility can be provided by dispatch-able generating devices (whether fossil-fuelled or renewable), storage capacities when they exist (mostly pumped-hydropower stations), interconnection among systems, and demand-side management. Variability of individual devices or technologies is dampened by geographical spread, as well as technology or resource versatility: for example, if there is no wind in one area, there might be some in another area; if the sun does not shine one day, the wind may blow instead; and if clouds in one region reduce solar electricity generation to a minimum, other roofs or regions might enjoy better weather, and so forth.

Another IEA study (Inage, 2009) confirms that in this range (10% to 12%) of penetration, PV does not significantly increase the need for electricity storage. The BLUE Map Scenario for Western Europe of ETP 2008 put the contribution of wind power at 27%. The assumed net wind power variability would require electricity storage capacities of 39.8 GW by 2020. Adding 12% PV in Western Europe by 2020, as originally suggested by the Solar Europe Industry Initiative (SEII) and considered in the High Ren Scenario of ETP 2010 would raise the requirement for storage only slightly to 42.8 GW.

Harnessing variable renewables

In *Harnessing Variable Renewables: A guide to the balancing challenge*, the IEA (2011c) studied a range of quite different power systems and showed how different the potential flexibility might be from one system to another, which is greater than usually thought. Similarly, the existing technical potential for flexibility is often much greater than the available potential – due to various barriers, which can be partially or totally removed (Figure 3.6).

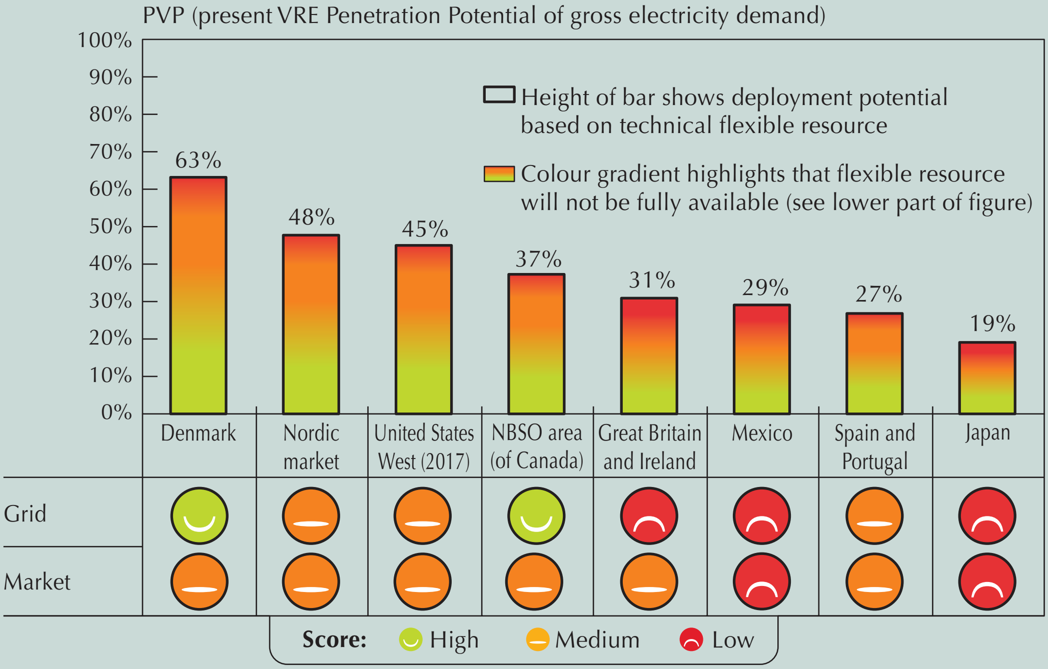
Drivers to make best use of existing flexible resources include strong and smart grids and flexible markets, but optimisation strategies would vary from place to place. Contrary to common belief, the introduction of variable renewable generating capacities does not require a "megawatt for megawatt" back-up, but rather holistic planning of flexible resources to cover net system variability. The addition of more flexible generating capacities as back-up might still be needed, but it is important to realise that such capacities will be run only rarely, and this is what makes building them fully compatible with low GHG emission scenarios.

In addition, significant current capacities, especially of flexible gas, will remain online in the coming decades, notably in industrialised countries (*e.g.* Italy, Japan, Spain, and the United States). Their capacity factor will decrease, either from now on or later (including after an increase as older coal plants are closed). To be kept alive, and ready as spinning reserves, flexible capacity might require some specific incentives, but in many cases there will be no or little need to build greenfield fossil-fuelled plants for backup.

This study shows that the variability of PV, which matches demand peaks better than wind power and is relatively predictable, is unlikely to raise substantive issues for managing grids. This is assuming PV generation achieves the levels considered in several scenarios of about 10% to 12% – although at different dates for different scenarios.

There will be, for sure, balancing costs for grid operators. In some areas, the total of distributed small-scale capacities can be greater than local demand could absorb at peak times. This means that the distribution and transport grids would have to work both ways. Most existing transformers allow only one-way conversions of high voltage (for transport) to lower voltage (for distribution). However, these costs will remain limited and not likely to prevent PV's 10% to 12% share.

Figure 3.6 **Present variable RE potential in various systems**



Note: NBSO stands for New-Brunswick System Operator.

Source: IEA, 2011c.

Key point

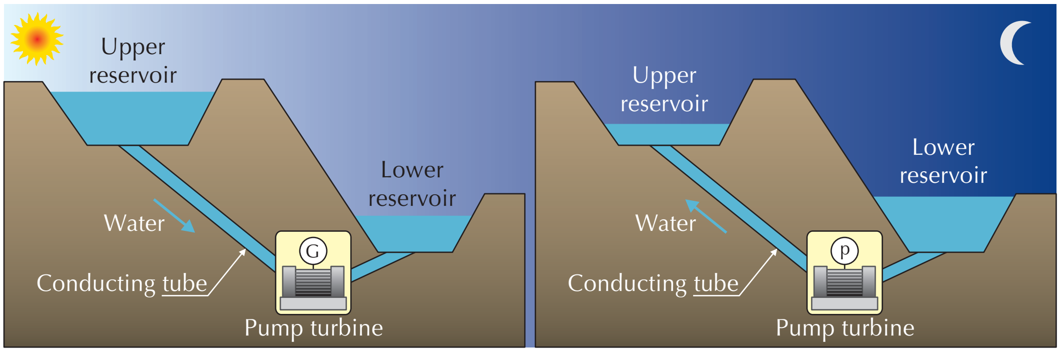
All electric systems already can handle some variable generation.

Storage options

Currently almost all global large-scale electricity storage capacities are in pumped-hydro storage, with about 150 GW in service and about 50 GW under construction. Water is pumped from a lower body of water to an upper one when excess electricity is available, and sent to the turbines when electricity is needed (Figure 3.7). Pumped hydro stations can be part of natural hydraulic systems, in which case they are both hydropower plants fed from natural waters, and pumped hydro plants. They can also be completely artificial and independent from natural rivers. The round-trip efficiency ranges from 70% to 85% – higher in more recent plants. Nevertheless, 80% efficiency means that 100 MWh of electrical output first requires the absorption of 125 MWh from the grid.

These plants were typically conceived to add some flexibility in electricity systems dominated by generating capacities with little economic flexibility. In France, for example, pumped-hydro storage stations are used to absorb nuclear power at night and generate electricity during demand peaks. Most of the plants worldwide are used on a daily basis, some only on a weekly basis.

Figure 3.7 **Principle of pumped-hydro storage, showing discharge (left) and charge (right)**



Source: Inage, 2009.

Key point

Pumped-hydro plants represent the bulk of electricity storage capacities today.

Recently, thanks to the emergence of variable-speed pumps, some plants are being used more efficiently and frequently, switching from pumping to electricity-generating modes several times a day, thus better fitting the requirement of absorbing variable renewables. The introduction of variable speed and power electronics also allows these plants to deliver more ancillary services to electric grids on various time-scales, *e.g.* frequency and voltage regulation, and reactive power.

Many other options exist for electricity storage, suitable for different needs on different timescales.[1] They include flow batteries or "redox flow cells", capacitors, dry batteries of various types (lead-acid, lithium-ion, sodium-sulphur, metal-air, zinc-bromine), flywheels, superconducting magnetic energy storage, compressed-air storage and others (Inage, 2009). They may all have a role for ancillary services at various levels of electric grids, especially the sodium-sulphur batteries for load management in isolated or end-point grids. But only compressed-air energy storage systems (CAES), with two plants currently in operation worldwide, represent a large-scale alternative to pumped-hydro plants.

CAES consists in using electricity to compress air to store it in large cavities, then letting the compressed air flow through a turbine expander to generate electricity when needed (Figure 3.8). Investment costs are in the same range as for pumped-hydro plants, but the round-trip efficiency of CAES at 60% at best is significantly lower. Indeed, current CAES plants lose heat during the compression of air, and need an external source of heat during its decompression to run a turbine expander, so they burn natural gas.

Advanced adiabatic compressed-air energy storage (AA-CAES) could eliminate or at least reduce the need for burning natural gas, and reach a round-trip efficiency in storing electricity of about 70%. The concept consists in storing separately the heat resulting from the compression of the air, and the air itself, then using the stored heat to warm the air being decompressed before it is sent

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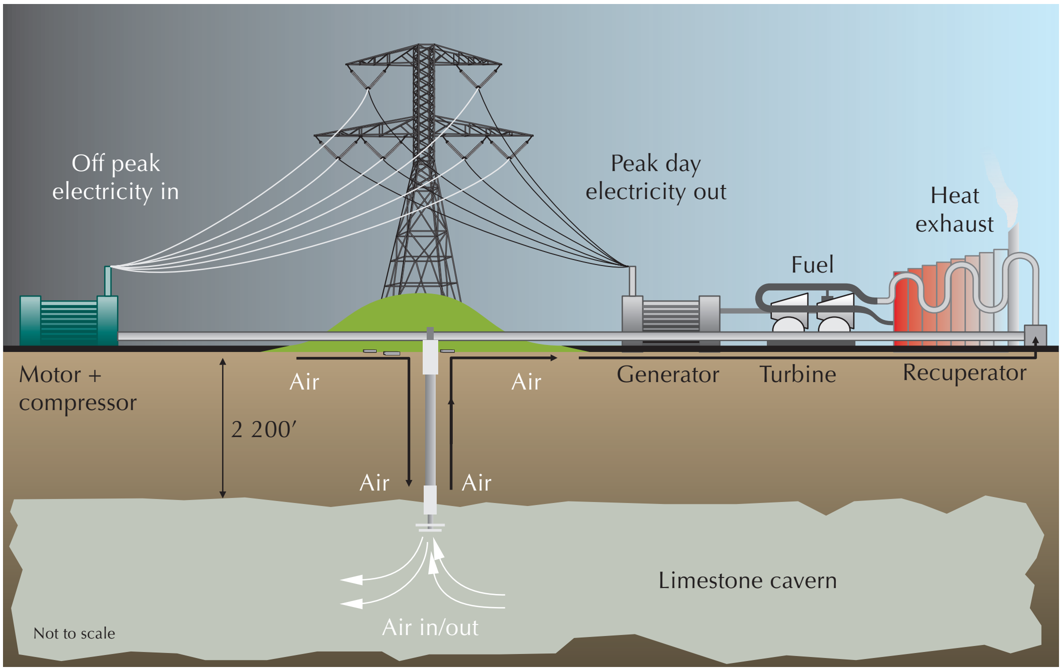
[1] *In areas where wind power and CSP co-exist or are linked together, such as Spain, one additional possibility to avoid curtailment of wind power could be to use the thermal storage capacities of CSP plants, which are partly unused in winter. Heating molten salts or another medium with electricity, then generating electricity from that heat, would not be very efficient (30% to 40% efficiency depending on the steam cycle). But it could prove better economics than dumping excess electricity, as the scheme would only require the additional investment of electric heaters in the thermal storage tanks.*

to a turbine expander. This promising technology could possibly take a share in the future global electricity storage facilities required by large-scale penetration of variable renewables (alongside pumped-hydro plants) particularly if its round-trip efficiency could be further improved.

Figure 3.8 **Compressed-air storage system**



Source: CAES Development Company.

Key point

CAES provides additional options for electricity storage.

The role of STE/CSP

Solar electricity is not necessarily as variable as the solar resource itself. Solar thermal electricity (STE) can use relatively cheap and very efficient thermal storage, which allows de-linking the time of sunshine collection and the time of generating electricity. In this decade, this characteristic is most likely to be used for shifting electricity generation to match peak demands, especially when they do not coincide with sunshine hours and are highly valued by grid operators, for producing electricity during peaks is always costlier. Progressively, storage will be used on a much larger scale to produce solar electricity during all times of mid-peak or shoulder loads, or even base load.

Morocco's demand curve provides a good potential example. Peak demand is driven by lighting and begins at sunset. It is met in part by pumped-hydro storage, in part by diesel plants. The government has launched a solar programme that aims to build 2 GW of solar power plants on five sites by 2019. Without storage, solar electricity would reduce coal consumption but would do little to reduce the high fuel costs incurred at peak times. With thermal storage, solar plants would significantly reduce fuel expenditures.

Morocco is not unique; other countries, mostly developing ones, such as India, show evening peaks. More often there is a relatively good match between the solar resource generation and peak demand, despite peak and mid-peak demand extending into the late afternoon and evening (Figure 3.9).

Photo 3.1 **The Gemasolar power tower near Sevilla (Spain)**

Source: Torresol Energy.

Key point

Molten-salts solar towers can generate electricity round the clock.

Seen by many as competitors, PV and STE should thus be viewed rather as complementary. PV is variable, STE can be made firm through thermal storage and fossil-fuel back-up.

STE technologies without storage may face tough competition from either concentrating PV (CPV) technologies or thin films, both of which are less sensitive than standard silicon modules to high ambient temperatures, in areas where the peak closely matches the sunshine. More often, STE with thermal storage should be compared with PV plus electricity storage. Such a comparison puts STE in a better competitive situation.

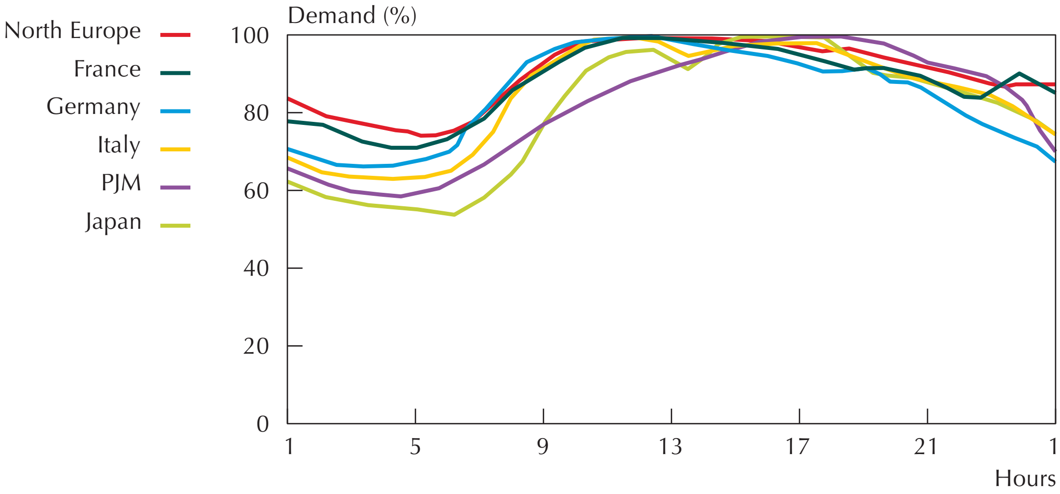
Hybridisation of solar fields on existing fossil-fuelled plants offers options – but only to STE – for introducing solar in the electricity mix at a lower cost than "full-fledged" STE plants, as the cost of non-solar specific parts of the plants (turbines, balance of plants, interconnection) would be shared with another technology, or be already paid for in existing plants. In the latter case, only the cost of the solar field and possible thermal storage would have to be considered (see Chapter 8), roughly halving the investment costs required to generate STE electricity.

Currently, STE is available only as concentrating solar power (CSP), which make economic sense only in areas with high DNI (see Chapters 2 and 8). The best examples of such areas are in Australia, Chile, Mexico, the Middle East, North Africa, South Africa, and the southwestern United States, but many other places are suitable, notably in China, India, Latin-America and south Europe.

Consistent with the BLUE Hi-Ren Scenario of *ETP 2010*, the IEA *Technology Roadmap: Concentrating Solar Power* foresees, by 2050, CSP contributing up to 40% of electricity generation in regions with very favourable conditions (IEA, 2010*d*); 15% or 20% for large consuming areas close to very favourable regions, and lower levels for other areas (Table 3.1).

New information on actual solar resource suggests Central Asia may be less favourable than expected, while the role CSP could play in China might have been assessed too cautiously.

Figure 3.9 **Comparison of daily load curves in six regions**



Note: PJM stands for Pennsylvania New Jersey Maryland Interconnection.

Source: IEEJ (The Institute of Energy Economics, Japan)/Inage, 2009.

Key point

In many areas, PV generation and peak demand show a good match.

Table 3.1 **Electricity from CSP plants as shares of total electricity consumption (%) in the BLUE Hi-Ren scenario, ETP 2010**

Countries	2020	2030	2040	2050
Australia, Central Asia*, Chile, India (Gujarat, Rajasthan), Mexico, Middle East, North Africa, Peru, South Africa, south-western United States	5%	12%	30%	40%
United States (remainder)	3%	6%	15%	20%
Europe (mostly from imports), Turkey	3%	6%	10%	15%
Africa (remainder), Argentina, Brazil, India (remainder)	1%	5%	8%	15%
Indonesia (from imports)	0.5%	1.5%	3%	7%
China, Russia (from imports)	0.5%	1.5%	3%	4%

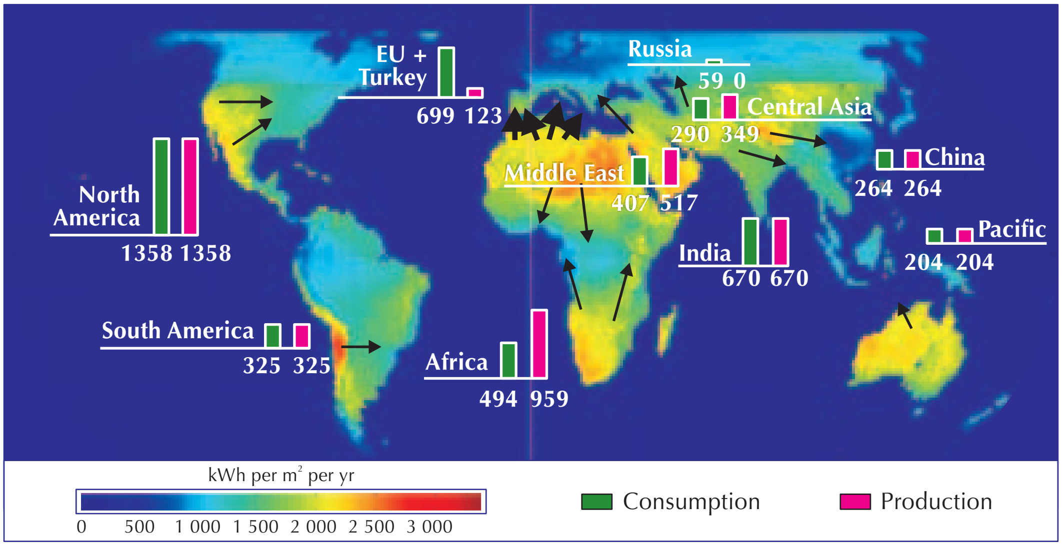
*Note: *Includes Afghanistan, Kazakhstan, Kyrgyzstan, Pakistan, Tajikistan, Turkmenistan and Uzbekistan.*

*Source: IEA, 2010*d.

Firm, dispatchable solar electricity from areas with strong DNI may benefit neighbouring areas through electricity transportation. Such links would most likely be to areas with high population and economic activities, which have greater electricity consumption. This is the essence of the so-called "Desertec" initiative (see Box: The EU-MENA connection). Long-range electricity transportation is not new, and has been most often deployed to link large reservoir hydropower dams to consuming areas. It is based on high-voltage direct-current (HVDC) technology. HVDC lines show only 3% electricity losses per 1 000 km, plus 0.6% losses in conversion at both ends, and have a smaller footprint than high-voltage alternate-current (HVAC) lines on lands. They can be deployed on sea floors at significant water depths, to link continents. HVDC lines can also be superimposed over an existing grid to increase interconnection capabilities; this is often referred to as super-grid.

In the BLUE Hi-Ren Scenario, the United States would be the largest producer and consumer of CSP electricity. Africa would be the second-largest producing area, exporting significant shares of its production to Europe. India would be the third producing and consuming region (Figure 3.10). Apart from the large electricity transfers from North Africa (and, to a smaller extent, Middle East) to Europe, potential exists for various long-range transportation lines, such as: from South-Western United States and Mexico to the rest of the United States, Peru and Chile to other Latin American countries, North and South Africa to central Africa, central Asia to Russia, Rajasthan and Gujarat to other parts of India, Tibet and Xingjian to other parts of China, Australia to Indonesia. West to East transfers could also take advantage of time zone differences to serve afternoon or evening peaks in some regions from others in their sunniest hours, and thus reduce the need for thermal storage.

Figure 3.10 **Production and consumption of CSP electricity (TWh)**



Note: Distribution of the solar resource for CSP plants in kWh/m²/y, and the production and consumption of CSP electricity (in TWh) by world region in 2050. Arrows represent transfers of CSP electricity from sunniest regions or countries to large electricity demand centres.

*Source: IEA, 2010*d.

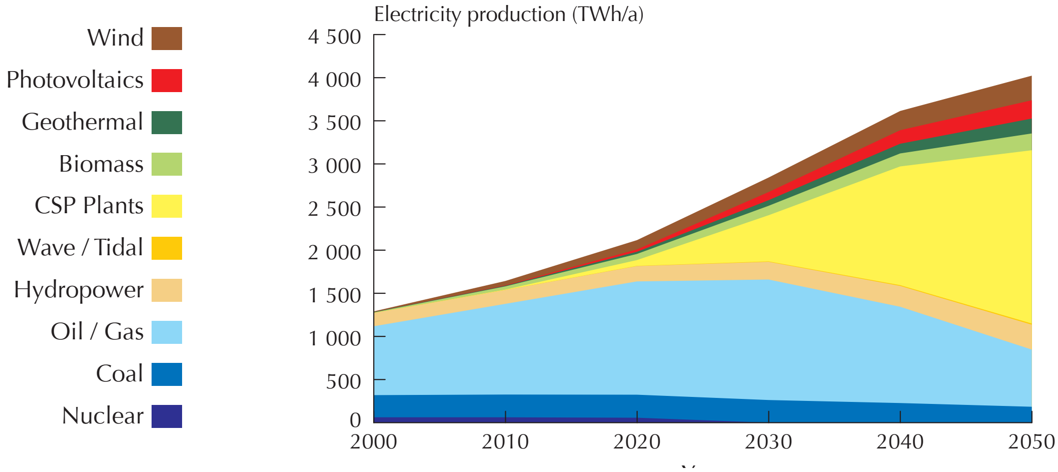
Key point

The United States will be the largest market for CSP followed by EU-MENA and India.

Various studies give STE/CSP a prominent role in electricity generation. In the Advanced Scenario of *CSP Global Outlook 2009*, the IEA SolarPACES programme, the European Solar Thermal Electricity Association and Greenpeace estimated global CSP capacity by 2050 at 1 500 GW, with a yearly output of 7 800 TWh, or 21% of the estimated electricity consumption in *ETP2010* BLUE Hi-Ren Scenario. In regions with favourable solar resource, the proportion would be much larger. For example, the German Aerospace Center (DLR), in a detailed study of the renewable energy potential of the MENA region plus South European countries, estimated that CSP plants could provide half the electricity consumption around the Mediterranean Sea by 2050 (Figure 3.11).

According to a recent study by PriceWaterHouse Coopers, Europe and North Africa together could by 2050 produce all their electricity from renewables if their respective grids are sufficiently interconnected. While North Africa would consume one-quarter of the total it would produce 40% of it, mostly from onshore wind and solar power. CSP plants would form the core of the export capacities from North Africa to Europe.

Figure 3.11 **Electricity generation from 2000 to 2050 and mix in 2050 in all MENA and South-European countries**



Source: DLR, 2005.

Key point

CSP can provide the bulk of the electricity in countries with good DNI.

The EU-MENA connection

The transfer of large amounts of solar energy from desert areas to population centres was advanced by the Algerian government when the country entered the IEA SolarPACES programme. This idea, further advocated by the DESERTEC Foundation, has inspired two major initiatives in Europe: the Mediterranean Solar Plan (MSP) and the DESERTEC Industrial Initiative (DII). The MSP aims to bring 20 GW of renewable electricity to European Union countries by 2020 from developing economies that participate. DII now comprises 19 shareholders (ABB, Abengoa Solar, Cevital, the Desertec Foundation, the Deutsche Bank, Enel Greenpower, E.ON, HSH Nordbank, Man Solar Millenium, Munich Re, M+W Group, Nareva Holding, Red Electrica, RWE, Saint-Gobain, Schott Solar, Siemens, Terna, UniCredit). DII aims to establish a framework for investments to supply the Middle East, North Africa and Europe with solar and wind power. The long-term goal is to satisfy a substantial part of the energy needs of the Middle East and North Africa (MENA), and meet 15% of Europe's electricity demand by 2050.

MENA's abundant sunlight will lead to lower production costs, compensating for additional transmission costs and electricity losses. The costs of production of firm and dispachable electricity in North Africa, currently assessed at USD 210/MWh and expected to be less than USD 150/MWh by 2020, plus its transport to the south of Europe, assessed at USD 20/MWh to USD 40/MWh, would make it an attractive way to comply with the current and future renewable obligations of European Union countries. The consortium Medgrid focuses on establishing the necessary HVDC transport lines.

From a MENA perspective, exporting electricity to Europe and providing the local population and economy with clean electricity do not conflict given the almost unlimited potential for solar electricity in the region. Indeed, exports to Europe may help secure the financing of CSP plants on the south shore of the Mediterranean Sea, which would generate electricity for both local and remote needs. The primary condition for the necessary investments is European countries offering to sign long-term power purchase agreements.

Concerns have been voiced about possible energy security risks for importing countries. Large exports, however, would require (by 2050) twenty to twenty-five 5-GW HVDC lines following various pathways. If some were out of order for technical reasons, or as a result of civil unrest or a terrorist attack, others would still operate – and, if the grid within importing and exporting countries allows, possibly compensate. In any case, utilities usually operate with significant generating capacity reserves, which could be brought on line in case of supply disruptions, albeit at some cost. The loss of revenue for supply countries would be unrecoverable, as electricity cannot be stored, unlike fossil fuels. Thus, exporting countries, even more than importing ones, would be motivated to safeguard against supply disruptions.

Economics of solar electricity

The PV industry has witnessed significant cost reductions in only the last three years. CSP plants, which have been developed only since 2006, have a longer lead time, and in the United States in particular have been facing administrative barriers. A rapid deployment with innovative designs and the emergence of new stakeholders in additional countries is now expected to unlock cost reductions.

Solar photovoltaics

PV costs have been reduced by 20% for each doubling of the cumulative installed capacity. The cost reductions are thought to result from manufacturing improvement and deployment as much as from research and development (R&D) efforts. There are excellent reasons to believe that this trend will continue, although it is not yet clear if a possible "floor cost" for full turn-key PV systems is in the USD 1.00/W range or significantly below (see Chapter 6 for a detailed discussion).

Most recent PV cost estimates are USD 3.12 per watt-peak (Wp – electric power under maximum solar irradiance) for utility-scale systems and USD 3.80/Wp for residential ones. These numbers are close to the actual PV systems prices in Germany, which currently represent half the global market. Significant deviations from these prices in other countries reflect the lower maturity of the markets and their financing systems, and/or the different levels of currently available incentives. High investment prices are expected to fall more rapidly than indicated by the learning curve if deployment is sustained and markets mature. Therefore, the rest of this analysis is based on German prices.

Market information indicates further reductions in PV investment costs, possibly achieving an additional 40% reduction in the coming years. This trend is projected to continue due to technological improvement and massive investment in new capacity, especially in Asia, provided that the current incentive systems are continued. By 2020, PV generation costs are expected to range from USD 81 to USD 162/MWh (utility-scale systems), USD 107 to USD 214/MWh (commercial systems) and USD 116 to USD 232/MWh (residential systems), depending on the site-specific solar irradiance level (see Chapter 6).

The levelised cost of electricity (LCOE) is the usual metric to compare the costs of different electricity generation technologies. It covers all investment and operational costs over the system lifetime, including the fuels consumed and replacement of equipment. In case of PV plants, the LCOE mostly reflects the initial investment costs, the cost of capital (including any discount rate), the irradiance level and the "performance ratio". The latter takes into account the losses due to the inverter, the effect of less-than-optimal direction and tilt of the modules, shadow effects and the like. Reasonable estimates for average performance ratios are 75% for residential systems, 78% for commercial systems, and 82% for utility-scale systems. Access to long-term debt financing has a significant impact on LCOE. For example, decreasing the interest rate from 9% to 4%, decreasing the equity-debt ratio from 40% to 30%, and increasing the loan term from 15 to 20 years together would decrease the LCOE by no less than 30% (an issue we will return to in Chapter 10).

In 2010, for large ground-mounted PV systems with 10% discount rate, the generation costs ranged from around USD 360/MWh in the north of Europe to USD 240/MWh in the south of Europe and most of the United States, and as low as USD 180/kWh in the Middle East, Northern Africa, and the southwestern United States.

Solar thermal electricity/concentrating solar power

Meanwhile, STE/CSP investments have not shown the same dynamism. In fact, they have lost their competitive advantage over PV except in places with exceptionally high DNI. This often also results from the value of storage not being reflected on markets. STE costs range from USD 4.20/W to USD 8.40/W depending on capacity factors and available solar resource (contrary to PV, the size of a CSP solar field can be adjusted to the resource for a given electric capacity). This leads to current electricity costs ranging from USD 170/MWh to USD 290/MWh. This situation evokes that of PV a few years ago, when some bottlenecks in manufacturing capabilities kept the prices higher than the learning curve suggested.

The current dynamics favour PV, which has a steep learning curve. It may appear that CSP will never catch up, but the maths of learning curve tells another story: a rapid growth rate of CSP from its current narrow basis would speed its cost reduction[2]. Detailed industry studies also find large room for technology improvements and cost decreases (see, *e.g.*, AT Kearney and ESTELA, 2010). A rapid advance of numerous projects in the United States and elsewhere, coupled with the introduction of efficient innovations (especially in the domain of CSP towers), and the emergence of new participants, are expected to lead to sharp cost reductions (see Chapters 7 and 8).

PV grid-parity

Electricity from residential and commercial PV systems is currently 27% more expensive than that from utility-scale, ground-based PV systems. This cost difference, largely due to greater margins throughout the supply chain, is expected to decrease sharply as competition increases. In the long term, residential PV systems may even become less expensive than ground-mounted PV, if PV is integrated at a very low additional cost in standard elements of the building envelope (see Chapter 6). It must be noted, however, that orientation and tilt are not always optimal, and shadows from the surrounding environment cannot always be suppressed.

Furthermore, residential/commercial PV competes with retail electricity prices, not wholesale prices. Retail prices include, among other things, distribution costs. In practice they are usually almost twice the cost of base-load bulk power. "Grid-parity" is reached when PV generation costs are roughly equal to retail electricity prices.

These costs are expected to be lower than electricity retail prices in several countries. This will allow PV residential and commercial systems to achieve parity with the distribution grid electricity retail prices in countries characterised by a good solar resource and high conventional electricity retail prices (noted "2nd competitiveness level" on Figure 3.12).

In some cases, grid parity will be reached before 2015. Islands are a case in point, as electricity generation is often based on costly oil-fired (diesel) plants. Madagascar, Cyprus, other Mediterranean islands, the Caribbean and the Seychelles represent significant examples, in this regard. In entire countries or regions, such as Italy or California, residential PV may also achieve grid parity in only a few years from now. The process will take more time in countries with lesser solar resource, but high electricity prices, and countries with good solar resource, but lower electricity prices. Some studies (*e.g.* Breyer and Gerlach, 2010) assume that grid parity would be reached in most of the Americas, Asia-Pacific and Europe by 2020. A more cautious assessment suggests that this will take place between 2020 and 2030, but likely not in the Northernmost European countries. Exceptions exist in countries where the electricity from the grid is significantly subsidised, such as Egypt, Iran, various MENA countries, South Africa, Russia and Venezuela, and, to a lesser extent, China and India. Another impediment to grid parity stems from the fact that retail electricity prices for households often do not reflect the true costs at all times, even if they do so on average. That is, prices are often "flattened", which may make them too high during off-peak demand times, and too low during peak demand times, compared with the production costs at those times. Producing electricity at

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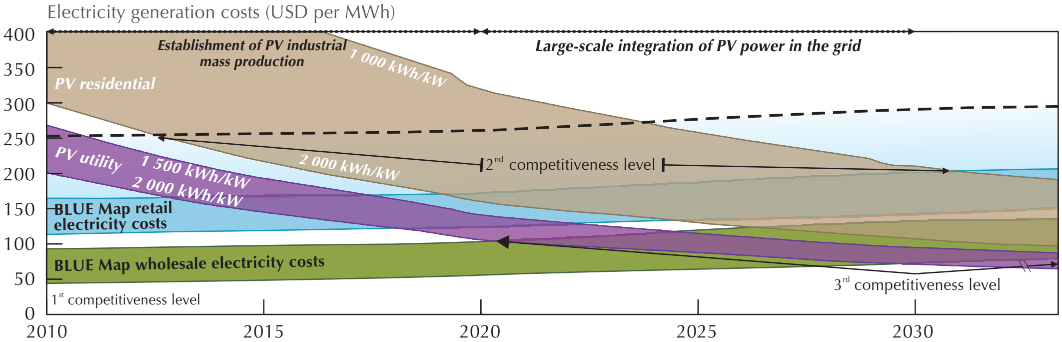
[2] *Adding another 40 GW to the existing PV capacity would reduce PV costs by 15%, with a 15% learning rate at system level. Adding 40 GW to the existing CSP basis, i.e. doubling the existing CSP basis more than five times, would reduce CSP costs by 40% with the less favourable learning rate of 10%.*

peak times is always costlier than base load electricity generation. In sunny and warm countries, the sunniest hours of the day usually correspond to the peak or mid-peak demand, but supply may or may not be priced high enough to reflect the full costs.

Figure 3.12 **PV competitiveness levels**



Note: The large orange band indicates PV generation costs of residential/commercial systems, which depend on the level of irradiance and performance ratios. These levels are represented by the electrical output of residential PV systems, so that 1 000 kWh/kW is obtained under an irradiance of 1 333 kWh/m^2/y on the modules. 2 000 kWh/kW for utility-scale corresponds to 2 353 kWh/m^2/y of irradiance. The large blue band indicates IEA forecast of retail electricity costs. The first level of competitiveness was for off-grid systems. PV is now approaching the second level of competitiveness, when PV generation costs are equal to retail electricity prices. The dark red band shows the IEA forecast of wholesale electricity costs, the dark blue band the costs of utility-scale PV generation. The third level of competitiveness will be reached when these two bands cross. Dates are indicative only, as the PV cost decreases are scenario-dependent.

Source: IEA, 2010c.

Key point

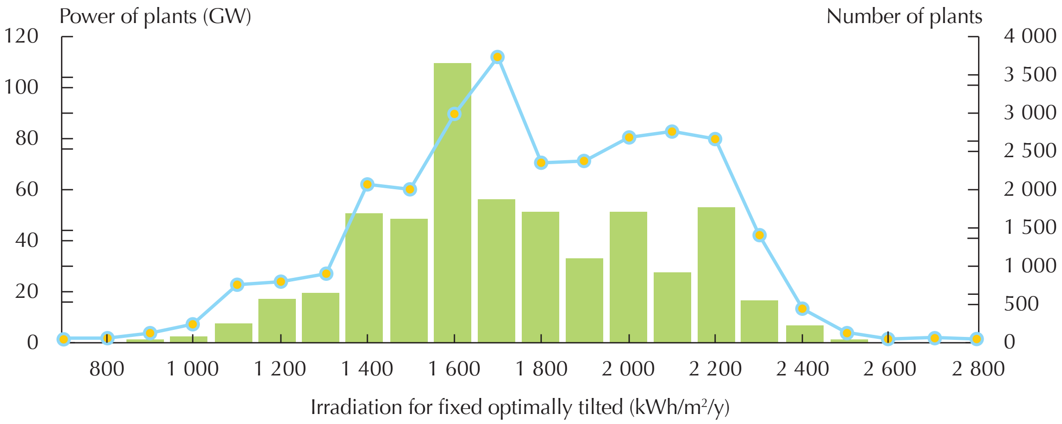
Residential and commercial PV will compete with retail electricity prices before 2020.

When PV and STE/CSP are becoming competitive with bulk power

If residential customers are not always given timely price signals, industrial customers tend to receive them, and utilities certainly know the differences between marginal costs for base load, intermediate load and peak load electricity generation. This is why some utility-scale (or "industrial") PV systems could find their way into bulk power markets sooner than expected by most analysts. This is likely to be the case especially where electricity generation is based on costly fuels (oil and diesel fuel) provided the solar resource is available during demand peaks. This is not likely to be the case in this decade for coal-based generation, which is most often base load, nor for gas-fired generation as the costs of natural gas have been decreasing as the result of the exploitation of shale gas in the United States.

Few industrialised countries make great use of oil in electricity generation – Italy and Japan (even before the Fukushima accident) being the most notable ones. Oil-rich Middle East countries, however, do burn oil to generate electricity, and other developing countries use numerous diesel generators and large amounts of diesel fuels to respond to rapidly growing demand peaks. A significant capacity (150 GW) of oil-based generators are located in very sunny regions of the world (Figure 3.13), but it is not clear whether peak demand consistently coincides with maximum or even significant sunshine. While oil-rich developing countries in hot regions have developed air-conditioning systems that drive demand, other sunny developing countries (for example, Morocco, Algeria, Libya or India) have not. Their demand peaks after sunset, driven by lighting. Even in industrial regions such as California, the thermal inertia of buildings perpetuates the demand for air-conditioning several hours after sunset, while demand for light adds to the peak, or at least mid-peak conditions.

Figure 3.13 **Oil power plants in operation and solar resource**



Note: Solar location of oil power plants as of end 2010. Power plants are geo-referenced and sorted by solar irradiance of fixed optimally tilted PV modules. Total oil power plants are 560 GW, of which about 150 GW is located in very sunny regions of more than 2 000 kWh/m²/y of solar irradiance.

Source: Breyer et al.*, 2011.*

Key point

Solar electricity in sunny countries will soon compete with oil-generated electricity.

Looking at the economics of electricity generation in oil-exporting countries and considering only extraction, refining and transportation, fuel oil can cost as little as USD 4.00 per barrel. Solar electricity cannot compete with this and may not for some time. However, considering the opportunity costs, *i.e.* the forgone revenues in consuming oil locally rather than exporting it, things change dramatically and those countries' costs are comparable with oil-importing countries. Oil prices have been on average over USD 100 in 2010. At USD 80 per barrel, PV electricity from utility-scale plants, if they are built for the same cost as in Germany, with Middle East solar resource, and solar thermal electricity (STE) from CSP plants are competitive with oil-based electricity generation.

Off grid

Cumulative off-grid PV electricity systems may represent about 3.5 GW of installed capacities today, mostly in industrialised countries, mostly for telecommunication relays and remote houses or shelters. Rural electrification is expected to represent the bulk of the installed capacities in many developing countries, but available information is scarce. At the end of 2009 capacities were estimated at 22 MW for Bangladesh, 10 MW for Indonesia, 7 MW (each) for Ethiopia, Kenya and Nigeria, and 5 MW (each) for Senegal and Sri Lanka. Each megawatt of solar home systems with an average size of 50 W offers basic solar electricity to 20 000 households, but these numbers pale when compared to the considerable demand in the developing world.

Indeed, electricity has yet to change the lives of 1.4 billion people who have no access to it today – more than was the case when Thomas Edison first popularised the electric light-bulb in the 1880s. Many more people suffer frequent shortages or voltage fluctuations, whether through insufficient generation capacities or weak distribution networks or both.

Fuel-based lighting is expensive, inefficient and the cause of thousands of deaths each year from respiratory and cardiac problems related to poor indoor air quality. It severely limits any visually oriented task, such as sewing or reading (IEA, 2006). Small quantities of electricity would provide light and power for education, communication, refrigeration of food and pharmaceuticals. More electricity would allow the development of economic activities.

The rate of electrification of the world population has increased dramatically in the last 25 years, mostly due to grid extensions in China. Where grids do not exist, there should be no systematic preference either for off-grid distributed systems or for grid extensions. The choice must rest on an analysis of the density of the population, lengths of cables, foreseeable demand, and the various generating means at hand, including their investment and running costs, and fuel expenditures (for a good example of such analysis, see *e.g.* Raghavan *et al.*, 2010).

Throughout most of the world, lack of access to grid electricity need not last forever. Electricity grids have many advantages. Grids require much less generation capacity than if each electricity usage had to be fed directly from an individual generating system. In most countries the total capacity subscribed by all customers is three to five times the total installed generating capacity, because not everyone makes use of all their available electric devices at the same time. Savings on the generation side usually more than offset the cost of building, maintaining and strengthening the electricity networks. It is not by accident that this model has spread all around the industrialised world.

Nevertheless, off-grid and mini-grid electric systems, totally or partly based on solar energy, whether PV or small-scale STE, offer, in many cases, a shorter route to electrification. This is especially true for low-density rural population in sub-Saharan Africa and Southeast Asia, where many of those lacking access to electricity live. As solar electricity costs go down, these markets will open further.

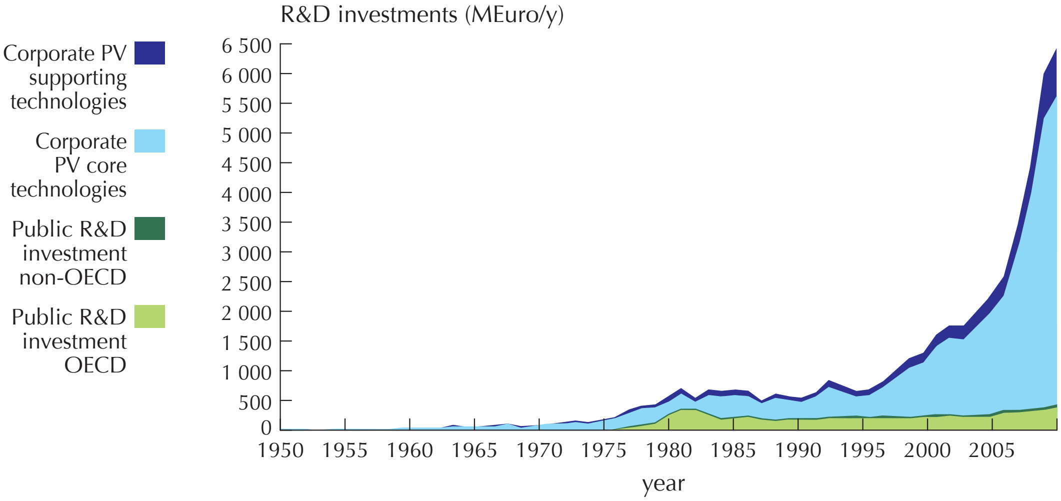
Policies

A wide range of policies might be considered for the support of large-scale deployment of solar electricity. Many have been spelled out in the Technology Roadmaps for solar PV and solar thermal electricity. The rationales and potential advantages and disadvantages of a number of them are discussed below.

- Support for research and development remains indispensible before new devices and approaches, such as those described in chapters 6 to 9, can reach their markets. Support for deployment drives considerable research effort from private companies, with private R&D expenditure growing sharply between the initiation of support and actual on-grid deployment, as the PV example shows (Figure 3.14).

- Specific support for innovation could take the form of loan guarantees, as successfully shown in the USA with large-scale innovative PV and CSP projects. Loan guarantees remove most of investors' and bankers' risks from investing in emerging technologies. This not only helps achieve financial closure of innovative projects, but also reduces the cost of capital and thus the projected total cost of electricity (including investment, interest rates and the projected life of the plant). Successful projects carry no cost for public finances.

Figure 3.14 **Public and corporate PV R&D expenditure (Million Euros)**



Source: Breyer et al., *2010.*

Key point

Deployment drives private R&D efforts.

- When there is a rush to install systems in rapidly growing markets, it increases the risk of technical mistakes in the choice and installation of solar electric systems. Governments should find ways to help industry develop product standards and increase installers' skills, while not introducing unfair and costly non-economic barriers to international product trade.
- Removing existing barriers to international trade, whether tariffs or non-economic, technical barriers, is likely to reduce the costs of solar electricity in many countries, especially in the developing world (see, *e.g.* OECD 2006).
- Access to the grid must be easy and streamlined for solar electricity producers. It includes three different aspects: the right for small producers to sell to the grid (*i.e.* the obligation for grid operators to buy it), the effective and rapid connection of new devices to the grid, and the priority given to access of solar electricity when available. In liberalised markets, this latter aspect usually does not raise issues, as capacities required to respond to the demand at any time are called in order of increasing marginal running costs – and those of solar electricity are among the lowest as they include no fuel – or little fuel in the case of hybrid solar thermal plants.

- Administrative bottlenecks may result from overlapping or conflicting official objectives and requirements, such as from relevant municipalities, regional authorities and government departments. One effective way to overcome such difficulties could be to organise regular meetings of a group of sufficiently high-level staff from the various relevant administrative authorities. Working together, they can overcome difficulties in ways that respect their specific objectives. Such practices appear to have helped solar projects survive administrative bottlenecks in California.
- Although solar electricity is on the verge of becoming cost-effective on grids in some markets, its deployment currently requires significant support in most. These support policies, the strengths and the weaknesses of the many forms they may take, and their overall costs are considered in detail in Chapter 10.
- The effective deployment of solar electricity is inseparable from the deployment of several other renewable electricity sources, notably wind power (especially under temperate and cold climates) and hydro power (especially under hot and humid climates). It is also inseparable from an important development of smart grids, *i.e.* grids that are able to convey electricity in both directions, from generation to transmission to distribution levels and vice-versa, while conveying market information as well as electricity. Policies relevant to the deployment of smart grids are detailed in an IEA technology roadmap (IEA, 2010*e*).
- Integrated thermal energy storage is a prominent feature of solar thermal electricity today, as it allows CSP plants to match demand peaks. Its value ought to be recognised and rewarded through market design and/or policy. By contrast, it appears that electric storage for PV electricity does not need to be developed in the next two decades. Large-scale electricity storage to facilitate large-scale penetration of solar PV electricity would need to be deployed only in the longer term, especially in temperate countries, where its deployment may in fact be primarily driven by the need to offset the variability of wind power, as shown in Chapter 11.

Chapter 4
Buildings

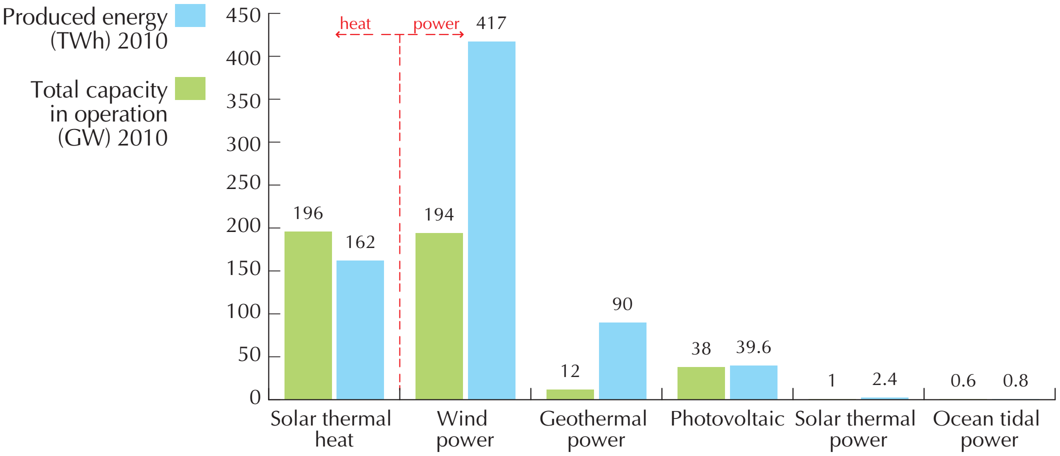
Today, residential and commercial buildings account for 35% of total global final energy consumption, notably for lighting, sanitary water heating, comfort ambiance, cooking and many electricity-driven devices. New buildings will see considerable reductions in these levels of consumption, driven by more stringent regulations. Refurbishment of many existing buildings will allow this total consumption to stay roughly constant despite demographic and economic growth, as the supply mix shifts from direct fossil fuel consumption to renewable energy and renewable-based electricity.

Buildings also offer large surfaces to the sun's rays. Capturing the sun's energy will enable buildings to cover a share of their heat consumption, a larger share of lighting needs and become significant sources of electricity. Furthermore, the increased use of thermal energy storage technologies in buildings will help improve demand flexibility and reduce the need for expensive electricity storage.

Solar water heating

Depending on the other uses of energy in buildings, domestic water heating can represent up to 30% of the energy consumed. Solar water heaters (SWH) represent one of the most profitable applications of solar energy today. They constitute the bulk of the current market of solar heating and cooling, which itself produces almost four times more energy than all solar electric technologies combined (Figure 4.1).

Figure 4.1 **Capacities and produced energy of "new" renewable energy technologies**



Source: Weiss and Mauthner, 2011.

Key point

Solar heat today provides four times more energy than solar electricity.

Simple systems such as thermo-siphon not protected against freezing, with flat-plate or evacuated tube collectors (see Chapter 7), can be installed on terraces and horizontal rooftops in mild climates (Photo 4.1 and Photo 4.2). Building integration of pumped systems allows storage for several days in stratified water tanks, where a back-up from another energy source is often installed. Manufacturers have overcome early technical issues, but installation requires trained and experienced installers. The most cost-effective systems cover 40% to 80% of the heating loads for sanitary hot water, however, covering 100% requires over-sized collectors and storage capacities. The additional cost is generally unjustifiable and over-sizing increases the risk of overheating, which could damage the collectors. Systems are usually designed to fully cover the low season for hot water demand (summer).

Photo 4.1 **Chinese thermo-siphon solar water heater**

Source: Popolon, Wikimedia.

Photo 4.2 **Solar water heaters in Kunming, China**

Source: Raffaele Miraglia.

Key point

Solar water heaters represent the bulk of solar heat, and most are installed in China.

Costs vary greatly according to climate conditions and the associated levels of complexity, as well as other factors such as labour. A SWH thermo-siphon system for one family unit consisting of a 2.4 m^2 collector and 150 litre tank costs EUR 700 in Greece, but EUR 150 in China (with no government support). In central Europe, a pumped system of 4 m^2 to 6 m^2 and 300-litre tank, fully protected against freeze, costs around EUR 4 500. Systems of this size might be used only for water heating, or also contribute – marginally – to space heating (as some do in the Netherlands), thereby increasing their value.

Solar domestic hot water systems cost in Europe from EUR 85/MWh to 190/MWh of heat, which is competitive with retail electricity prices in some countries, if not yet with natural gas prices. These costs are expected to decline by 2030 to EUR 50/MWh to 80/MWh for solar hot water systems.

In China, Cyprus and Turkey, low-cost solar water heaters are already an economic alternative for households. In Israel, they are ubiquitous and save 6% of total electricity demand. In

South Africa, electric water heating accounts for one-third of the power consumption of the average household. The government has identified the massive deployment of solar water heaters as one effective option to avoid electricity shortages, and launched a programme to install one million solar water heaters by 2014 (Photo 4.3). When large regions are compared, China is the market leader not only in absolute terms but also on a per capita basis, followed for the first time in 2009 by the Middle East.

Photo 4.3 **Solar water heaters in South Africa**

Source: Weiss, 2011.

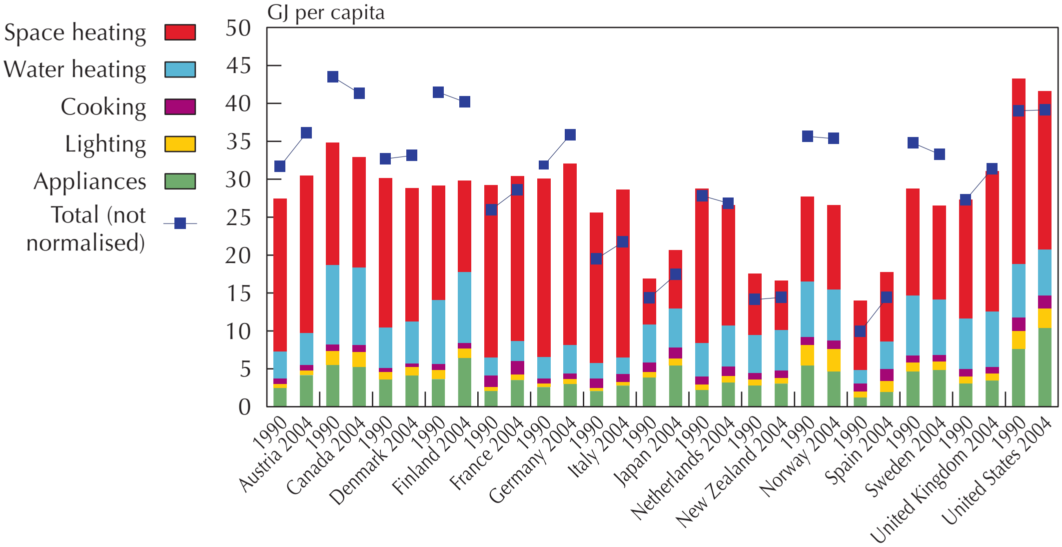
Key point

Solar water heaters can help avoid electricity shortages in developing economics.

Energy efficient buildings and passive solar

The relative importance of the various sources of energy consumption in buildings varies by region, climate, level of development and sector. In IEA member countries, most energy in the building sector is used for space and water heating, while energy consumption for cooling is generally modest. Even in the United States, with its mature air-conditioning market, energy consumption for cooling is only around 8% of energy consumption in residential buildings and 13% in commercial buildings. In France, a temperate European country, space heating accounts for 70% of energy consumption in residential buildings, sanitary hot water for about 10%, specific electricity consumption for 10% and cooking for 8%. In sunnier Spain, water heating represents one-third of the total demand for heat in housing. On average, space heating alone represents half of the energy used in households, down from 60% twenty years ago (Figure 4.2).

Figure 4.2 **Energy consumption in buildings in select IEA countries (GJ per capita)**



Note: Consumptions are normalised to offset yearly climatic variations.

Source: IEA, 2008c.

Key point

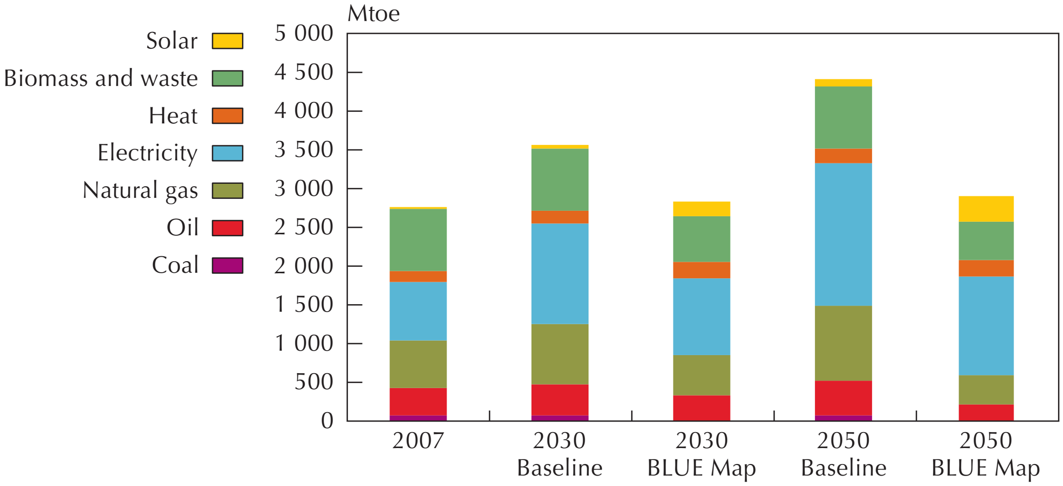
In developed countries space heating accounts for half the energy used in buildings.

It follows that the areas for improvements in efficiency and application of solar energy in buildings differ considerably from country to country, and within large countries. Commercial buildings use more electricity for lighting and specific equipment. In less developed countries, cooking is by far the largest energy need. In emerging economies under warm climates, with little or no space heating needs, water heating accounts for a much larger share but cooling may come first (and still represents a significant source of future energy demand growth).

In the Baseline Scenario of *ETP 2010*, global final energy demand in buildings increases by 60% from 2007 to 2050. This increase is driven by a 67% rise in the number of households, a near tripling of service sector building, and higher ownership rates for existing energy-consuming devices and increasing demand for new types of energy services.

In the BLUE Map Scenario, global buildings sector energy consumption in 2050 is reduced by around one-third of the Baseline Scenario level in 2050, which makes it only 5% higher than in 2007. This can be achieved only by retrofitting most existing buildings, along with other measures. The consumption of fossil fuels declines significantly, as well as that of traditional biomass, to the benefit of modern renewable energies, mostly as direct heat, and electricity (Figure 4.3).

Figure 4.3 **Building sector energy consumption by fuel and by scenario**



Note: Heat here represents only commercial heat, in district heating.

Source: IEA, 2010a.

Key point

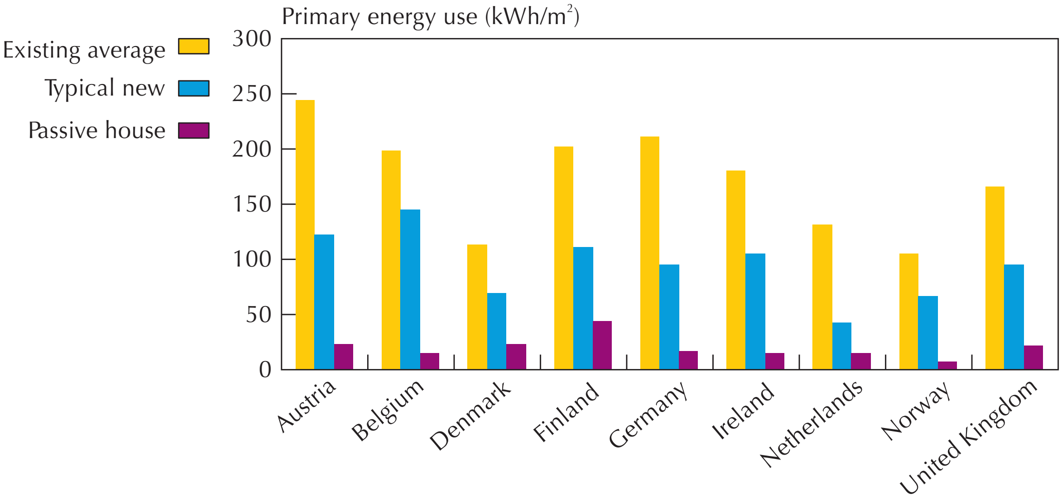
Direct fuel use in building is considerably reduced in the BLUE Map Scenario.

The largest energy savings by end use in the BLUE Map Scenario in the residential sector come from space heating. In the service sector, the largest savings come from lighting and miscellaneous energy use. Highly energy efficient buildings have very low heat losses both through the building envelope thanks to insulation and improved windows, and through air exchange thanks to heat recovery systems. Current building regulations ensure that new buildings are more efficient than existing ones, but much greater energy efficiency improvements are feasible with "passive" solar concepts (Figure 4.4).

Passive solar buildings also maximise the free inputs of solar energy as heat during cold seasons, and protect the building's interior from too much sunshine in the warm seasons, while allowing enough daylight to reduce the need for electric lighting (see Box: Day lighting). Letting the sun heat buildings in winter and letting daylight enter them to displace electric lighting is the least-cost form of solar energy. In some cases passive solar design can help cut up to 50% of heating and cooling loads in new buildings. The necessary additional investment costs are low when the products are mass-manufactured, and are largely compensated for by the reduction in capacity of the heating/cooling system they allow – not to mention the energy bill reductions for decades to come.

Buildings should also be thermally massive (*i.e.* with greater capacity to absorb and retain heat) to avoid overheating in summer and oriented preferably toward the Equator. The glazing should be concentrated on the equatorial side, as should the main living rooms. Passive cooling techniques are based on the use of heat and solar protection techniques, heat storage in thermal mass, and heat dissipation techniques. However, excess thermal mass could lead to under-heating in winter, and should be avoided.

Figure 4.4 **Yearly primary space heating use per dwelling in selected European countries**



Source: Kaan, Strom and Boonstra, 2006; IEA, 2010a.

Key point

Newly built houses are more energy efficient, but could do much better.

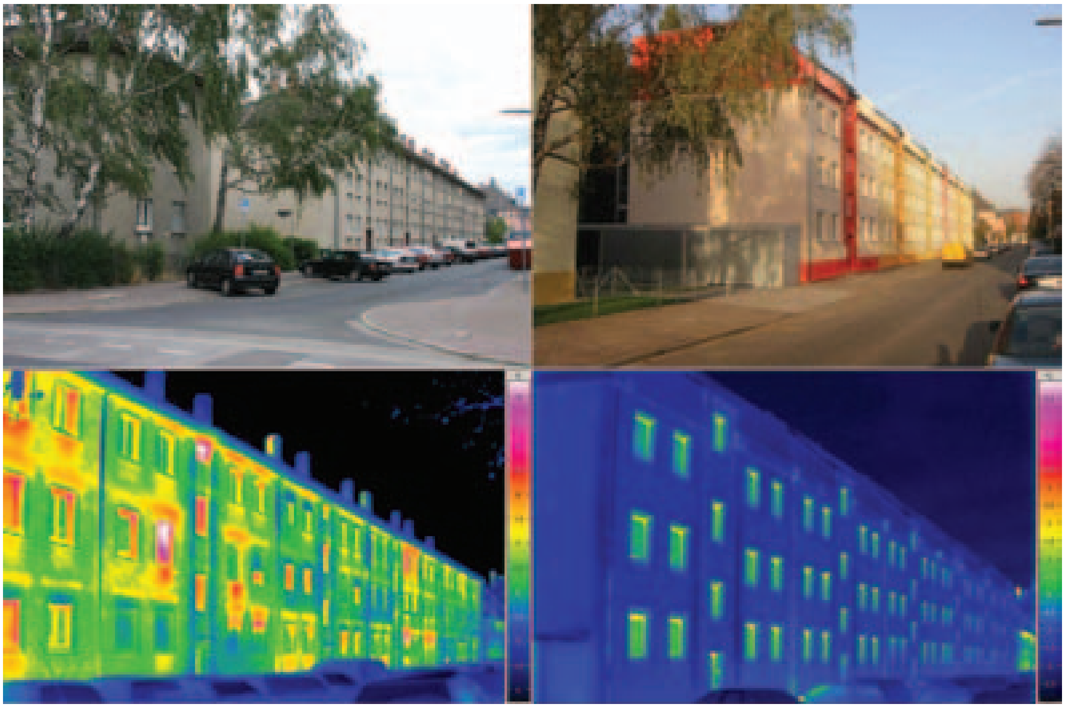
Insulation technologies, very efficient windows and materials, and the art and knowledge of conceiving very efficient buildings under a great variety of situation – cold, temperate, hot and arid, hot and humid – exist and are widely available, though not necessarily mobilised (see, *e.g.* Haggard *et al.*, 2009). They mix up-to-date software and hardware, and breakthrough technologies of various kinds, with traditional knowledge inherited from before cheap oil inundated the planet.

These technologies and practices are also available for refurbishing existing buildings. Especially when visual characteristics need to be left unchanged, refurbishing may not bring the energy consumption of existing buildings down to the level of newly built ones, but would still represent considerable improvement. A multi-dwelling building of Haussmann's era in Paris, for example, consumes about 410 kWh/m^2/y for space heating. The most recent regulation for new buildings sets the maximum consumption at 50 kWh/m^2/y (with some local variations). This includes space and water heating, cooking and specific electricity. Insulation of the roof, the ground floor, external insulation of the back façade, the change of all windows and doors, and the introduction of a more efficient boiler brings the space heating consumption down to 120 kWh/m^2/y. This is more than twice as much as a new building, but almost 70% less than before refurbishment. The street façade looks very much the same as before.

Full refurbishment from outside has been systematically developed in several countries in northern Europe, with very convincing results. One project in Frankfurt reduced heating loads to one-eighth their previous level while increasing available housing area (Photo 4.4). The energy consumed for space heating has been reduced by 87% in this building. High-rise buildings can also be retrofitted and considerably improved. In La

Défense near Paris, the First Tower, built on the remains of the Axa Tower, requires five times less energy for space heating and twice less for air-conditioning than its predecessor. If renovation from outside is impossible, renovation from inside can take place but usually only through deep refurbishing as most of the plumbing, electricity and finishes will have to be redone. This will often entail some loss of interior space, as thin insulation materials are still under development. Limited renovation (changing windows, insulation of roofs and sometimes of the ground floor), does reduce energy consumption, but to a smaller extent. It has been argued, however, that continuous energy efficiency improvement based on scheduled refurbishment would ultimately drive more global energy cuts for similar expenses than more radical but costlier "all-at-once" renovation (Acket and Bacher, 2011).

Photo 4.4 **Frankfurt refurbishment using passive house technology**



Notes: Top photos show the building before and after the refurbishment. Bottom images show infrared visualisation of the heat losses before and after the refurbishment.

Source: Passive House Institute Darmstadt, government-funded by the Ministry of Environment, Energy, Agriculture and Consumer Protection of the State of Hesse.

Key point

Building renovation can reduce energy expenses sevenfold or more.

Day lighting

"Day lighting" describes the practice of maximising during the day the contribution of natural light to internal lighting. The difficulty is to provide ambient light while avoiding glare, and also overheating the buildings' interiors. Day lighting may use windows of many types, skylights, light reflectors and shelves, light tubes, saw-tooth roofs, window films, smart and spectrally selective glasses and others. Hybrid solar lighting, developed at the Oak Ridge National Laboratory in the United States, links light collectors, optical fibres, and efficient fluorescent lights with transparent rods. No electricity is needed for daytime natural interior lighting, but when the sunlight gradually decreases fluorescent lights are gradually turned up to give a near-constant level of interior lighting.

Lighting represents an important share of electricity consumption in industrialised and emerging economies, but also important costs to consumers in least-developed countries (IEA, 2006). Solar light is naturally a prime candidate to replace daytime artificial interior lighting (see, *e.g.*, *IEA-SHC, 2000*).

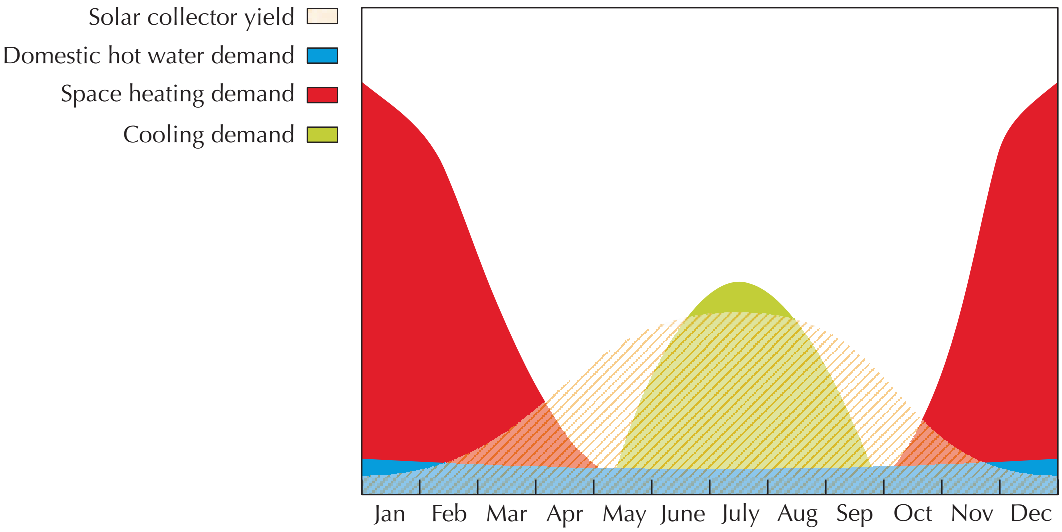
Active solar space heating

Active solar space heating requires more complex installations based on solar collectors of various types and some storage (see Chapter 7). Unglazed air or water collectors can be used as "solar walls". They offer a transition between purely passive and active systems. Combi-systems covering a larger fraction of heating loads (as well as water heating loads) may require collectors from 15 m^2 to 30 m^2 in Europe. Heat costs about USD 225/MWh to USD 700/MWh. The cost-effectiveness of solar space heating systems does not only depend on solar resource, but also on the heat demand. In France, for example, space heating systems offer better economic performance in the east or the north while solar water heaters are more profitable in the south. The most cost-effective applications are usually found in mountainous regions or countries, such as Austria and Switzerland, where reduced atmospheric absorption of solar energy drive up both the heating loads and the solar resource. Only in Austria and Germany has the share of combi-systems in single-family houses recently exceeded 50% among all newly-built solar thermal systems. It has exceeded 70% in Spain, but only for multi-family dwellings.

At country level, recent experience suggests that costs are reduced by 20% when the cumulative capacity doubles, according to the European Solar Thermal Industry Association. The technology is still improving rapidly in many applications, and most national markets are still immature, leaving ample room for cost reduction. The costs are expected to decline by 2030 to USD 140/MWh_{th} to USD 335/MWh_{th} for combi-systems, and USD 40/MWh_{th} to USD 70/MWh_{th} for large-scale applications (>1 MW_{th}). Cost reductions will come from the use of less costly materials, improved manufacturing processes, mass production, and the direct integration into buildings of collectors as multi-functional building components and modular, easy-to-install systems.

Active solar heating faces an intrinsic difficulty: over the year, the demand for heat is in inverse proportion to the availability of solar energy. Solar collector yield is maximum in summer and minimum in winter (Figure 4.5). The higher the intended coverage of the heat demand, the larger the collector area must be, but the cost-effectiveness of the marginal square metre of collector area decreases as more energy must be dumped when it is not needed. Heat demand for water is less variable during the year, although demand for hot water for body comfort increases in winter while more heat is required to warm the mains water. All in all, combi-systems, even with large hot water storage tanks (1 000 m^2 to 3 000 m^2) usually cover only 15% to 30% of the total demand for space and water heating – the higher range probably being reached more easily in multi-family dwellings, thanks to some mutualisation of the demand.

Figure 4.5 **Yearly pattern of solar yield *versus* demand for space and water heating and cooling**



Source: ESTIF, 2007.

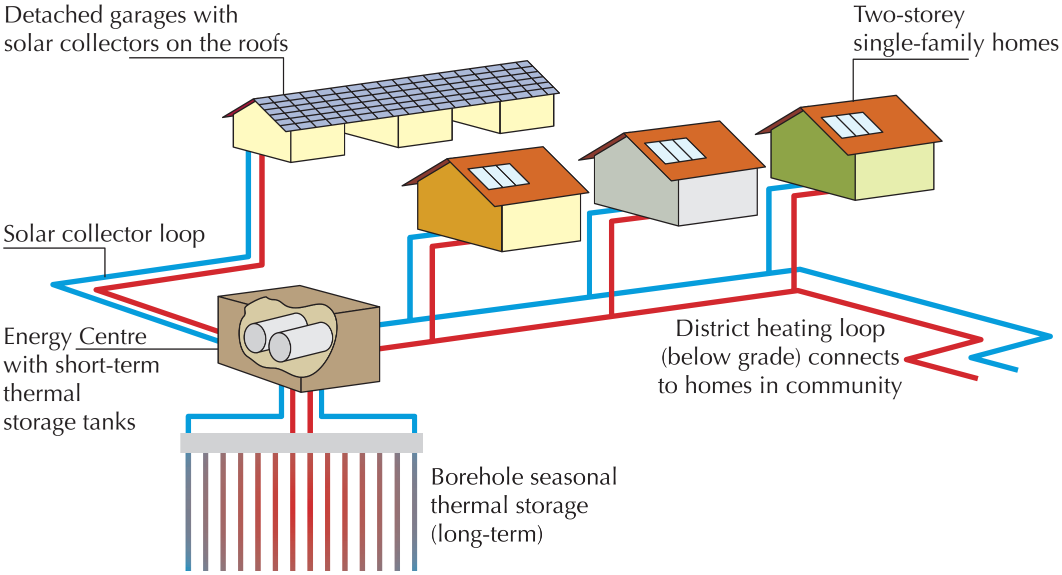
Key point

The solar resource is minimal when the demand for space heating is maximal.

Worldwide, there are hundreds of examples of high-temperature seasonal storage, usually with hot water tanks in the basement. One such example is the solar district heating system developed at Friedrichshafen in Germany 15 years ago. Together with 2 700 m^2 of solar collectors, it uses a long-term heat storage unit (designed as a cylindrical reinforced concrete tank with a top and bottom having the form of truncated cones) entirely buried in the ground. The system provides about half the yearly need for water and space heating of 570 housing units, at a cost of USD 63/MWh.

A more recent example is the Drake Landing Solar Community development in Okotoks, Alberta, Canada: 52 efficient houses, each with its own solar water heater, powered by solar collectors on the garage roofs. Solar heated water is pumped into 144 boreholes, 37 m deep, thus heating the ground to up to 90°C. During the winter, the hot water flows from the storage field to the houses through a distribution network, where it exchanges heat with air blown in the house (Figure 4.6). In this example, 90% of the space heating loads and 60% of the water heating loads are met by the sun.

Figure 4.6 **Solar seasonal storage and district loop, Drake Landing Solar Community**



Source: Minister of Natural Resources, Canada (NRCan).

Key point

Comprehensive storage systems for solar energy make heating more affordable for a district.

Inter-seasonal ground storage, when not used in combination with heat pumps, seems more appropriate for large installations in district heating and multifamily dwellings. This results from the ratio of the surface area of the "envelope" of the storage over its volume, which decreases as the volume gets bigger. Heat losses are a function of the area of the envelope, and of the temperature. As heat is exchanged with the immediate ground environment and spread over a larger volume, its temperature decreases. To minimise heat losses one must either minimise the surface area through which heat exchanges take place – as in large storage systems for district heating – or reduce the temperature to levels that make it usable only with heat pumps.

Solar-assisted district heating is spreading in countries where district heating already provides a large proportion of the space heating demand, such as Sweden, Denmark and other central and Northern European countries. Despite the lower solar resource, the cost is only about USD 56/MWh on average, as the solar fields are installed on existing district heating networks. Other countries have ambitious scenarios with high penetration of active solar space heating technologies (*e.g.* the "full R&D and policy" scenario of the European Solar Thermal Industry Federation. see Dias, 2011). These largely rely on the development of affordable, efficient and compact thermo-chemical storage systems for individual housing units.

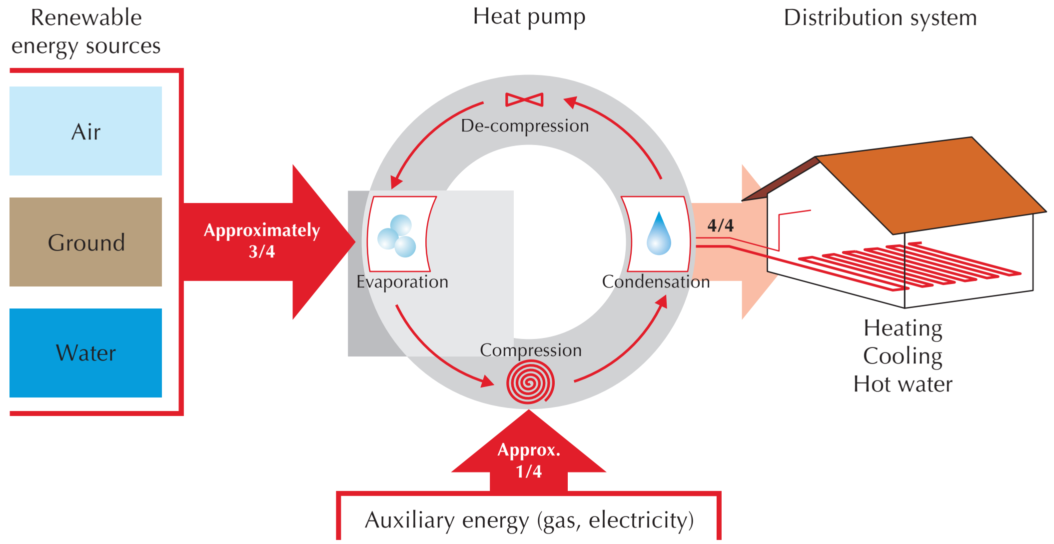
Solar water heating and space-heating systems increase fourfold between the Baseline and BLUE Map Scenarios – mostly based on SWH. One variant of the BLUE Map Scenario, the BLUE Solar Thermal, assumes that low-cost compact thermal storage is available by 2020 and that system costs come down rapidly in the short term. Active solar thermal technologies thus become the dominant technology in 2050 for space and water heating. The BLUE Heat

Pumps variant, by contrast, assumes the development of ultra-high efficiency air-conditioners and faster cost reductions for space and water heating applications. In such case heat pumps, which take most of their resource from the surrounding, renewable "ambient energy" would become the dominant heating technology by 2050. This would still allow a significant role for direct solar energy, as we shall see.

Heat pumps

A heat pump works in a similar way to a refrigerator. A refrigerator cools food by extracting their heat, which is then released through a condenser. In the case of the heat pump for space heating, the evaporator extracts heat from the environment (water, ground, outside air or waste air) and adds this to the heating system through the condenser (Figure 4.7). In other words, heat pumps extract heat from a relatively cold medium and lift its temperature level before introducing it into a warmer environment. Apart from the electricity running the pump, itself ultimately turned into heat, the origin of the energy is renewable – solar for air-source heat pumps (ASHP) and "horizontal" ground-source heat pumps (GSHP) or surface water-source heat pumps (surface WSHP), and a mix of solar and geothermal for "vertical" GSHP or deep WSHP, depending on the depth at which they collect the heat.

Figure 4.7 **How heat pumps work**



Notes: Whether used for cooling or for heating, heat pumps use a gas refrigerant, which a pump circulates between two heat exchangers separated by a barrier (the wall of a house or of a refrigerator). In practice the heat exchangers are just hollow metal coils, one is known as an evaporator and the other is known as a condenser. As the refrigerant enters the condenser it is compressed, which raises its temperature. Then as it flows through the condenser it gives off this heat to its cooler surroundings. After the condenser, the cooled but still pressurized refrigerant is allowed to expand as it reaches the evaporator. This drops its temperature to the point where it is cool enough to absorb heat from its surroundings. The gas then returns to the condenser where the cycle repeats.

Source: EHPA/Alpha Innotec.

Key point

Heat pumps transfer heat from the cold outside to the warm inside.

Most heat pumps are run from electricity. They introduce more heat in the building than an electric heater would do. An electric heater would never convert more than 100% of electricity into heat. Heat pumps do, however, because they "pump" the heat from the cold outside to the warm inside. Their coefficient of performance (CoP) measures the ratio of heat transferred to consumption of the pump. An important measure is the annual average CoP, also called the seasonal performance factor (SPF). The CoP varies considerably with the design of the whole system, and its conditions of use, but the basic principle is simple: the greater the rise in temperature, the lower the CoP. For example, a heat pump using outer air at 0°C and feeding small radiators, originally designed for some boiler with water at 60°C, would have a CoP of only 1.5 to 2. If the lift is even greater, the CoP may fall below unity. Indeed most of the energy is then brought in by transforming into heat the work of the pump, which is an inefficient and costly way of making heat from electricity. By comparison, a ground-source heat pump using heat from the soil at 12°C and feeding a heating floor (with a large heat exchange area) with water at 35°C, can exceed CoP of 6. The implicit assumption in Figure 4.7 is of a CoP of 4, which would be the SPF of good domestic ground-source or larger air-source heat pumps in cold climates. Of course, the heat pump itself must be well designed and run smoothly with an electronic inverter and variable speed, not simply an on-off device.

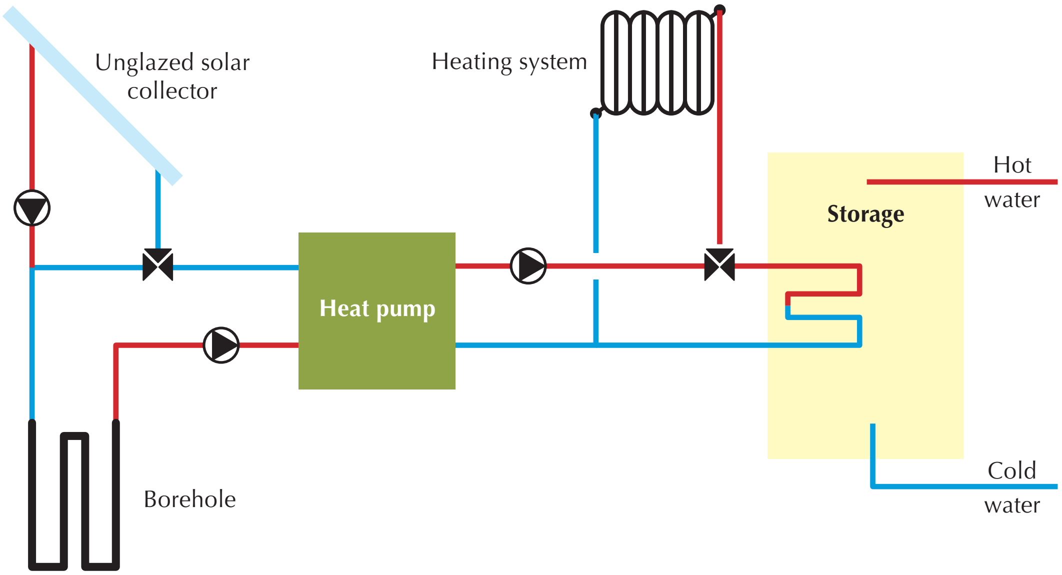
Which heat pumps justify the term "renewable energy", and should all the heat they deliver be considered renewable? The European Union stated its position in the Directive of the European Parliament and the Council of 23 April 2009 on renewable energy. First, heat pumps are considered renewable provided that the final energy output significantly exceeds the primary energy input required to drive the heat pumps. In practice, electric heat pumps would need to have an SPF greater than the ratio of the primary consumption for electricity production. This has been calculated as an EU average, over the total gross production of electricity in Europe, plus 15%, *i.e.* greater than 2.875 with the current electricity mix. The energy considered renewable is the heat delivered, minus the electricity consumption of the pump. The share of renewable energy in any given heating system increases with better SPF.

In cold climates, ground-source heat pumps should be preferred and their working conditions optimised. In new buildings, the choice of heating floors is easy. In renovations, better insulation could allow existing small radiators to heat the interior with a smaller working temperature than before, but increasing the radiator area would still be advisable to further reduce this working temperature.

In the ground, temperature conditions are quite stable all year round, because the heat is very slow to move through the soil and the renewable energy from either above (the sun) or below (the earth's interior warmth) keeps temperatures roughly constant. However, because the heat is so slow to move through the soil, in the immediate neighbourhood of the boreholes and pipes from the heat pump, temperatures will progressively diminish during the winter as the heat pump locally removes the heat. A colder area is thus created, and the CoP of the heat pump will progressively diminish as well, thereby affecting the SPF.

There are several options to avoid this. One is to warm the working fluid by a few degrees before it enters the heat pump. This can be done by a relatively small solar collector surface area. Another is to inject heat into the ground in summer, so as to start the heating season with a higher temperature around the boreholes. This can be done by cooling the building in summer, either reversing the heat pump (simple valves can do this), or making the fluid in the radiators or heating floor directly transfer heat to the colder transfer fluid in the ground. This "free cooling" option saves electricity in not running the compressor of the heat pump since no temperature lift is required. The third option is to send some solar heat from the collectors – again, a relatively small area may suffice – into the boreholes during summer. This heat will be efficiently recaptured by the heat pump in winter, while the solar collectors can also be used to pre-heat the fluid that enters the heat pump, further increasing its efficiency (CoP). This can be done with glazed or unglazed collectors, as shown on Figure 4.8. Even for single-family houses, heat losses in this combination are limited by the relatively low working temperatures of this sort of inter-seasonal ground storage.

Figure 4.8 **Combination of GSHP with solar collectors**



Source: Henning and Miara/Fraunhofer Institute for Solar Energy Systems.

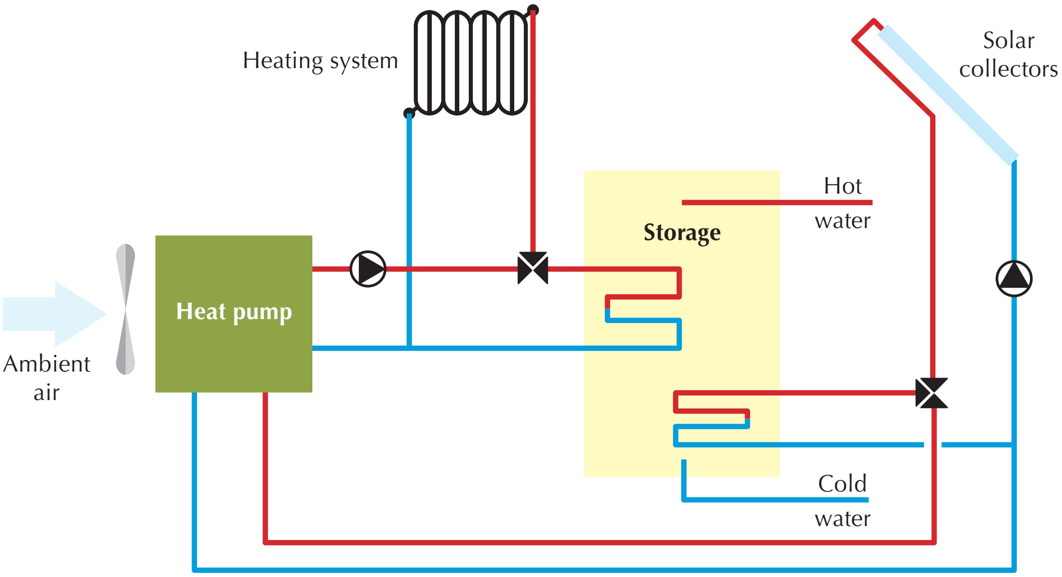
Key point

Unglazed solar collectors can increase the efficiency of ground-source heat pumps.

Indeed, there are many ways to combine solar heat and heat pumps. These combinations increase the solar fraction of water and space heating, up to 50% or more, with limited solar collector areas and without the need for very large heat storage systems. They increase the SPF of heat pumps and can provide long-term ground temperature stabilisation to GSHP.

Another combination of great interest in urban renovations and many other cases where access to the ground is limited links solar collectors with the less efficient ASHP (Figure 4.9). Glazed collectors are likely to be preferred in this case for better performances, to compensate for the likely lower temperature of the ambient heat. This raises the SPF by about 20%. A more sophisticated combination that added an intermediate latent heat storage system could lift the SPF by 40%.

Figure 4.9 **Combination of ASHP with solar collectors**



Source: Henning and Miara/Fraunhofer Institute for Solar Energy Systems.

Key point

Effective use of air-source heat pumps may require glazed collectors.

Heat pumps and solar thermal systems can either complement or compete with each other. Heat pumps specially designed for domestic hot water may even rival solar water heaters. In mild climates, these thermodynamic devices usually recycle low-temperature heat from laundry rooms or garages and use it to warm water. In warmer climates, they would take the form of "de-super-heaters", using the rejected heat from air-conditioning systems.

Heat pumps are not always run by electricity. Thermally driven heat pumps exist, and are usually large and fuelled by natural gas in the commercial sector. In theory, thermally driven heat pumps could be run by solar heat, but the mismatch between resource and demand makes the investment economic only for reversible heat pumps used for both heating and cooling, as shown below. In this case, solar heat will save a little additional electricity during the heating season, and a lot more during the cooling season.

Space cooling, air-conditioning

Passive solar cooling is the cheapest option, mixing traditional practice with modern technology. It includes the design of houses and other buildings, protection against the sun in summer, thermal masses, ventilation, solar chimneys, use of solar walls to let fresh air from the polar side enter the buildings, shadows, evaporation of water (deciduous trees provide both), fountains, ponds and other attractive features. It extends to the design of streets and cities.

Most widespread air-conditioning systems today are chillers, which work exactly as heat pumps for space heating but function in reverse, moving heat from the interior to the outer environment. A simple unique investment for both heating and cooling is a reversible heat pump. Run by electricity and rejecting the heat in the outer air, most have not much to do with solar energy, unless the electricity itself comes from the sun. Efficiency of cooling is always lower than heating with heat pumps, as the mechanical energy of the heat pump is not part of the desired result. Rejecting outdoor heat when it is quite warm further increases the energy consumption (here again, ground-source reversible heat pumps could be preferable). Rejecting the heat in a colder environment increases the SPF of the heap pump during cooling. This heat, of solar origin, is not lost in this case, as when it is rejected in the air; instead, a significant proportion can be recaptured during the winter. Finally, at times where only mild cooling is needed, the heat pump itself can be bypassed; direct heat exchanges between the fluid from the borehole and the fluid that cools the buildings can further reduce electricity consumption.

Thermally driven heat pumps can also be run on solar heat. As often pointed out, the demand for cooling matches the solar resource better than the demand for heating. Most current solar cooling installations are based on absorption machines with closed cycles, with only a few based on adsorption closed cycles.[1] Most are in Europe, especially small-scale systems in Spain. A handful of large-scale open-cycle systems (based on desiccant materials) directly produce cooled air, while solar energy regenerates the sorbent. One effective use of these systems is to dry the air for environmental comfort in hot, damp climates. Running air-conditioners or chillers from the sun reduces the need for electricity to run a compressor, but some electricity is still needed for pumps and fans. The electrical CoP usually reaches 8, *i.e.* one kWh of electricity is used to produce 8 kWh of cold. The thermal CoP (kWh of cold produced from 1 kWh of heat from the solar collector) is less than 1, except for double-effect chillers run by concentrating solar collectors.

The economics of solar collectors is improved if they provide domestic hot water, space cooling in summer, space heating in winter and, where possible, refrigeration services. There are many large-scale examples in various countries; the world's largest system is being built in Singapore for a new campus of 2 500 students. However, solar thermally driven air conditioning and cooling systems are still under development, in particular for individual houses. The investment costs are five to ten times higher than standard air-conditioning systems, and, despite electricity savings, the cost-effectiveness is low. Standard cooling systems run from PV panels, perhaps with some cold storage, may be less costly.

Significant improvements seem needed in either compact thermal storage and/or solar thermally driven cooling systems, to make large-scale solar thermal collectors cost-effective, by comparison to renewable electricity-driven, reversible heat pumps (preferably GSHP). Combined with smaller solar collectors they can cover a significant proportion of water heating loads, helping to boost the performance of the heat pumps and stabilise long-term ground temperatures.

One emerging technology that could enhance the value of large-scale solar thermal systems is the co-generation of electricity with lower temperature heat for space or water heating from no- or low-concentrating collectors at temperatures of about 160°C.

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[1] Adsorption is the bonding of a gas or other material on the surface of a solid; in the absorption process a new compound is formed from the absorbent and working fluids.

Solar-assisted reversible heat pumps, combined with better insulation, can considerably reduce the need for burning fuel in houses and flats. This has been seen recently in Norway, where more than 30% of detached dwellings have been equipped with heat pumps in the last ten years, contributing to a halving of heating oil consumption in the residential sector. But such combinations still consume more electricity than pure solar systems. Increased electricity consumption is not necessarily an issue, if its generation is almost entirely renewable, as in Norway with hydro power, or becomes predominantly solar.

Zero-net and positive energy buildings

Traditionally, buildings have been considered energy consumers; it is now widely recognised that they can be energy producers. Building envelopes offer considerable surface areas to sunshine. The European PV Industry Association (EPIA) calculates that “with a total ground floor area over 22 000 km^2, 40% of all building roofs and 15% of all facades in EU 27 are suited for PV applications.” Over 1 500 GWp of PV could technically be installed in Europe, which would generate annually about 1 400 TWh, representing 40% of the total electricity demand by 2020. In built-up areas, PV systems can be mounted on roofs (known as building-adapted PV systems, BAPV) or integrated into the roof or building facade (known as building-integrated PV systems, or BIPV). Most solar PV systems are installed on homes and businesses in developed areas. By connecting the building to the local electricity network, owners can feed clean energy back into the grid, selling their surplus energy to help recoup investment costs. When solar energy is not available, electricity can be drawn from the grid.

The IEA *Technology Roadmap: Solar Photovoltaic Energy* foresees that more than half the global PV capacity from now to 2050 will be installed on buildings in the residential and commercial sectors, producing a little less than half the total PV electricity needed (IEA, 2010*c*).

Modern PV systems are not restricted to square and flat panel arrays. They can be curved, flexible and shaped to the building’s design. Innovative architects and engineers are constantly finding new ways to integrate PV into their designs, creating buildings that are dynamic and beautiful and that provide free, clean energy throughout their life. Manufacturers are also beginning to mass-produce elements of building envelopes that integrate PV, or solar thermal, such as tiles or pre-manufactured units (Photo 4.5).

On a smaller scale, research and experiments have investigated how to integrate CSP in buildings; a new wave of development may emerge if non-concentrating solar thermal technologies with thermal storage proves to be a workable option.

According to EPIA, 20 m^2 PV systems in a sunny region (global irradiance at least 1 200 kWh/m^2/y) would produce enough electricity to fulfil the specific electricity needs of a family of two to three people for a year, with an excess in spring and summer, and a deficit in winter (Figure 4.10). This is one approach to the concept of zero-net energy buildings, or even positive energy buildings; *i.e.* very efficient buildings able to produce, from their envelope, as much energy as they consume, if not all the time, at least on yearly average. (The natural warmth of people inside becomes significant at this level of efficiency.)

Photo 4.5 **Manspach church (Alsace, France) renovated using photovoltaic tiles**

Source: Daniel Dietmann, Saint-Gobain Solar.

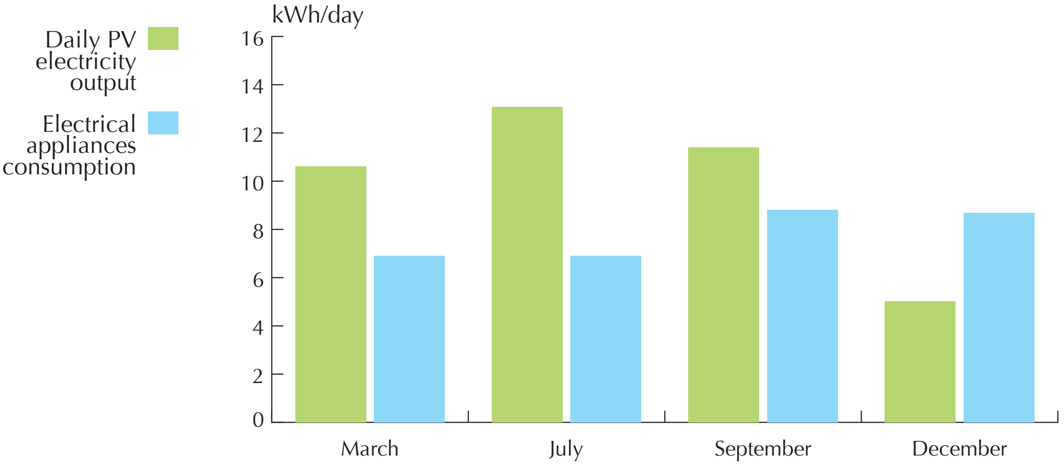
Key point

Solar PV and thermal can be concealed and integrated in easy-to-assemble systems.

In an era of energy-producing buildings, the grid would then serve as a storage system, from the viewpoint of each producer-customer. As shown in Chapter 3, a PV penetration of about 10% would not create significant issues for the grid operators as a result of its variability. Some work would be needed on the grids to facilitate the minute-by-minute transfer of electrons from buildings with excess to those running in deficit even if they were some distance away. The current at the connection linking grid and building would need to go from distribution to transmission levels, and not only, as at present, from transmission to distribution levels.

The IEA PVPS (Photovoltaic Power Systems) programme studied the potential for generation of electricity from PV integrated in, or adapted to, buildings in 14 countries in 2002 and compared this technical potential to the electricity consumption of these countries in 1998 (in total, not only in buildings). This assessment is based on reasonable assumptions to evaluate the surfaces available on façades and roofs, the effects of shading, the orientation and tilt of the collecting surfaces in relation to the available solar irradiance, and an efficiency ratio of 10%, which represents the low end of PV efficiencies (Table 4.1). This technical potential assessment does not account for the issues of variability and cost (IEA-PVPS, 2002).

Figure 4.10 **Daily production of a 20 m²-PV roof and appliance electricity consumption of small family in sunny region**



Source: Sunrise project/EPIA.

Key point

PV production on individual houses can cover the electricity consumption of appliances.

Table 4.1 **Potential for solar electricity generation on buildings as share of electricity consumption in 1998**

Australia	**Austria**	**Canada**	**Denmark**	**Finland**	**Germany**	**Italy**
46.1%	34.7%	30.6%	31.6%	19.4%	30.1%	45.0%
Japan	**Netherlands**	**Spain**	**Sweden**	**Switzerland**	**United Kingdom**	**United States**
14.5%	32.2%	48.0%	19.5%	34.6%	30.7%	57.8%

Source: IEA-PVPS, 2002.

Key point

Building-integrated or -adapted PV can cover from 15% to 58% of electricity loads.

The achievable levels of generation depend mainly on the building areas available, solar irradiance and electricity consumption. They are highest for the United States, and lowest for Japan, mostly as a result of the available building area per capita. This building area includes residential and commercial buildings, but also agriculture buildings and industrial buildings. Their proportions vary from country to country, but residential comes first with more than half the overall potential, followed by commercial buildings in North America by a large margin and in Japan, while in several European countries and Australia agriculture buildings come second, except for Germany and Italy where industrial buildings come second. Overall, these estimates suggest that solar electricity generation on buildings can reach substantially higher levels than seen in most projected scenarios to 2050. Note that the results presented in Table 3.1, as well as the comparison of electricity needs and PV production shown on Figure 4.10 do not take into account the possible substitution of large amounts of heating fuels by electricity in heat pumps.

Cooking

Cooking usually represents less than 10% of energy consumption in buildings in IEA member countries. By contrast, it represents a major component of consumption in developing countries, and contributes to indoor air pollution and its associated lung and eye diseases, as well as major difficulties of fuel-wood collection, and desertification when harvesting exceeds regeneration.

In industrialised and emerging countries the solutions rest on efficiency improvements, notably allowed by electric induction techniques, which could allow more solar and renewable energy. Direct solar cooking techniques are not considered for day-to-day use.

In developing countries things can be very different. Techniques for cooking at different temperature levels range from low-cost hotboxes to concentrating parabola (see Chapter 7).

Attempts to make these devices popular have so far had mixed results, as regular use requires major changes in families' habits and lifestyle. Community kitchens have been quicker to discover the merits and advantages of solar cooking, especially fuel savings, as in India (Photo 4.6) with the Scheffler dishes described in Chapter 7.

The need for an integrated approach

Buildings are large consumers of energy, but there are many options to reduce this consumption and at the same time transform buildings into significant energy producers. Energy-efficiency improvements and solar options must be associated to minimise the consumption and maximise the production of renewable energy, in order for zero-net energy buildings and even positive energy buildings to become a reality. The appropriate combination depends on climatic conditions, heating and cooling needs, use of the buildings, solar resources, available space, and the proportions of new building and renovation.

There is no one-size-fits-all solution, but there are some guiding principles. Energy efficiency rests primarily on insulation and optimal thermal masses. Passive solar heating and cooling, and day-lighting, must be considered first. Solar hot water generation can produce high proportions of domestic hot water needs and substitute for electric water heating in clothes and dish washing machines. Solar space heating and cooling, and appropriate storage, need to be further developed. Combinations of reversible (preferably ground-source) heat pumps, relatively small solar collector fields, and building integrated or building adapted PV production may offer viable options in a relatively large variety of situations in temperate to cold countries.

Photo 4.6 **Solar steam cooking system at Shiridi for 20 000 meals**

Source : Deepak Gadhia.

Key point

Solar cooking works best for community kitchens in developing countries such as India.

Zero-net energy buildings or positive energy buildings will likely have on their roofs and façades, whether very visible or concealed, both solar thermal collectors and PV collectors (Photo 4.7). Solar thermal is significantly more effective in capturing the energy from the sun (70% peak efficiency) than PV (20% peak efficiency), as long as the heat is effectively used for heating water or space heating, directly or with heat pumps. These applications do not require very large collector surface areas, so they leave enough room for PV systems, which have the advantage of production being usable either locally or by distant customers, so it is never wasted – an option usually not available for solar heat.

The photo also shows that the tilt angle of solar thermal collectors, identifiable by their storage tanks, is greater than that of PV modules in the foreground. This maximises heat collection in winter, when the sun is low on the horizon. This suggests that placing the PV modules on the roof and integrating thermal modules in the façades could help maximise the collection of solar energy.

Another option is to use hybrid photovoltaic and thermal (PVT) modules, which combine PV generation and heat collection on a single surface. This can be done with glazed water collectors or with unglazed air collectors mounted as "transpired walls" covered with a PV layer on their sunny side (see Chapter 7). While it is unclear whether this combination works well for both systems, as some manufacturers claim, it certainly extracts the most energy from a given collector surface area and represents an interesting option when the available surface area is limited, as in densely populated areas. If larger proportions of solar energy are to be captured in the future in and from building envelopes, PVT modules could become an imperative, as the available space on buildings is limited. Another possible advantage of PVT modules is that they could help make affordable the cooling of buildings at night through radiative heat exchange with the sky.

Photo 4.7 **An installation of solar PV and thermal collectors on the same roof**

Source: SunEarth Inc.

Key point

Solar PV and thermal are both needed on positive energy buildings.

The most critical energy issue in the industrialised world is probably not to assess whether new buildings will have a small net consumption or a small net production, but rather to accelerate the use of renovation of the existing building stock to reduce consumption, and re-roofing with solar technologies to increase energy production.

In the developing world, the energy balance of new buildings is much more important, particularly in light of the weakness of centralised energy networks in many countries. Passive cooling options for both new build and renovation are of primary importance. Architects and real estate developers need to combine the use of modern materials and knowledge with traditional know-how on making the most from the local environment and resources. Building-adapted and building-integrated PV, and to some extent STE, probably offer a considerable potential under sunny skies, as do solar water heaters. Finally, solar cooking can usefully substitute for fossil fuels and inefficient biomass use.

A truly integrated approach would probably need to go one step further, and look closer at building-integrated PV generation and the way it is being used, in particular in conjunction with the emergence of electric and plug-in hybrid vehicles (as is further considered in Chapter 5). One aspect that deserves consideration is the nature of the current: alternating (AC) or direct (DC). Grid-integrated systems all have an inverter, which converts the DC from the modules into AC that can be exchanged with the grid. However, a number of appliances in buildings use DC. The wide variety of voltages makes a distinct DC circuit in houses impractical. If batteries from electric vehicles become an important customer/reservoir for PV modules, it might be worth having some direct current link between the modules and the batteries, instead of undergoing a double DC-AC-DC conversion, with its inevitable losses.

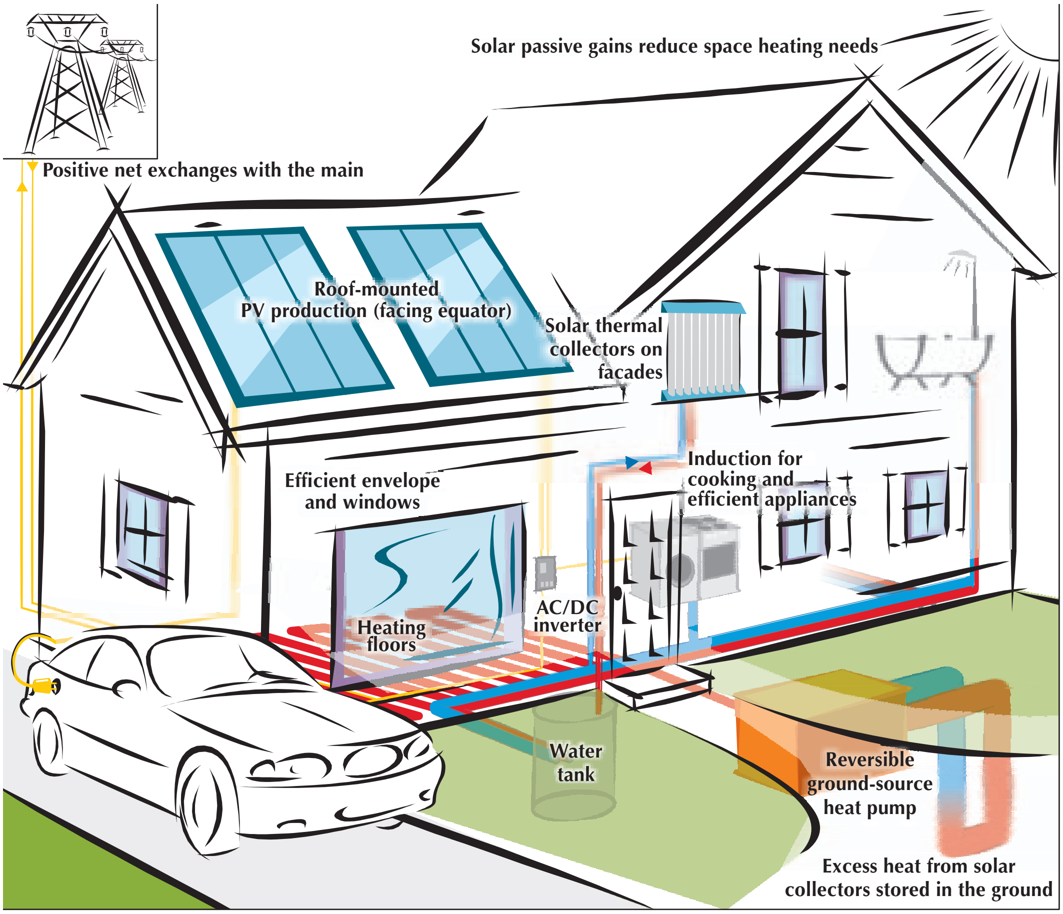
Another area of investigation could be optimal population/housing density. Greater population density reduces heating losses and transport needs, but also reduces the surface area available for collecting solar energy. Small detached dwellings offer larger surface areas for a given overall volume than bigger buildings, but require much more transport. If walls and windows are inefficient, densely packed urbanism can reduce the losses. With highly efficient envelopes that produce more energy than they allow to escape, smaller buildings could be preferred. Ultimately, the optimal choice – only from an energy point of view – could depend on the energy consumption in transport, and its origins.

Policies

Policies for deploying solar energy solutions in buildings are quite diverse. There may well be a need for broad policies to support solar electricity, and others to support direct solar heat in various forms. The latter policies will be further developed in the forthcoming *IEA Technology Roadmap for Solar Heating and Cooling*, to be published in 2012.

- An integrated approach to the deployment of solar energy should aim to foster the deployment of the whole set of technologies that would facilitate the use of solar energy in buildings, and the use of buildings as decentralised generators of solar electricity. This may include: new energy standards for new buildings; the promotion of heat pumps, passive solar designs and solar water heating; and speeding the refurbishment of existing buildings (Figure 4.11).
- It should also include measures to encourage and facilitate the development of relevant skills for project developers, architects, thermal engineers, and other building professionals.
- Product certification and guarantees of results, developed in cooperation with the industry, are essential to gain consumer confidence in new products. Streamlining and harmonising certification procedures, if possible at an international level, is key to creating global, efficient product markets. Various policy aspects have been addressed in the IEA *Technology Roadmap: Energy-Efficient Buildings* (IEA, 2011*d*).
- Environmental non-governmental organisations have suggested tying the authorisation to benefit from building-integrated or building-adapted PV feed-in tariffs to the refurbishment of existing buildings to reduce heating loads (see, *e.g. France Nature Environnement*, 2011). This may prove counter-productive, as the dynamics and participants in both developments are significantly different. Artificially combining them may impede both, instead of making one support the other. However, emerging market products that could play both roles, from PV thermal hybrid collectors to roof elements that bear PV collectors while ensuring good thermal insulation, could and perhaps should receive specific incentives.

Figure 4.11 **An integrated approach to the development of solar energy in buildings**



Key point

Energy efficiency and solar energy technologies must be closely associated.

- A common difficulty in achieving building refurbishment (including addition of solar water and passive or active space heating systems) is split incentives. An example is when landlords have to pay the investment costs while most of the benefits accrue to tenants (or costs accrue to real estate developers and benefits to future inhabitants). Specific regulation could overcome such issues, such as the solar ordinances that make using solar energy to provide for a share of domestic hot water needs, or energy-efficiency regulation in buildings stringent enough to effectively promote solar energy. Other, more market-oriented possibilities could include developing use of third party financing and energy service companies. Allowing for targeted revisions of existing renting contracts, in countries where they are usually prevented by regulation, may also help solve the issue for the common benefit of landlords and tenants.

Making buildings energy producers as much as energy consumers requires that electricity companies must purchase customer-generated power at a fair price, which should be made mandatory by local or national jurisdiction.

Photo 4.8 **Installing a solar air heating system**

Source: Solar Wall.

Key point

The envelopes of new buildings both conserve and produce thermal and electric energy.

Chapter 5
Industry and transport

The progress of efficient electricity-based techniques in industry and transport may become the main vehicle for introducing solar energy more broadly in industry. Some companies may recognise the benefits of producing solar electricity at or near their industrial facilities. Prospects for direct use of low-temperature solar heat are considerable in the food industry, and noteworthy in several other industries. Use of high-temperature heat from concentrating solar rays may warrant further investigation, beyond possibilities in desalination for fresh water production.

Industrial electricity

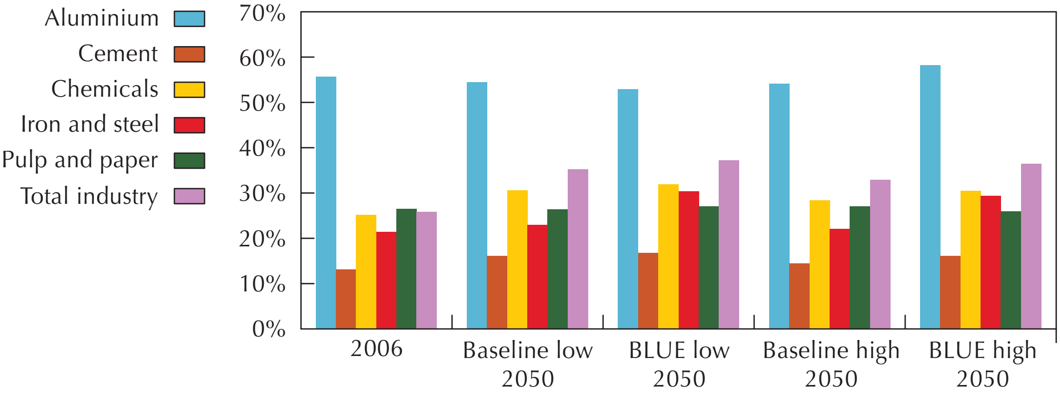
Manufacturing industry accounts for approximately one-third of total energy use worldwide. Electricity constitutes just over one quarter of this energy; fossil fuels and biomass (for about 8% to total final energy in 2007) provide the rest, mainly used as process heat but also for self-generation of electricity, including co-generation of heat and power.

As in other consuming sectors, if a larger share of grid electricity comes from renewables in general and solar energy in particular (as seen in Chapter 3), so will the electricity consumed in industry. One way to get more solar and renewables in the industrial energy mix is thus to develop efficient uses of electricity – with a progressively growing solar and renewable share – to displace fossil fuel uses. Many technologies are now available that can replace fossil fuels for a great diversity of industrial processes. Examples include freeze concentration instead of the thermal process of evaporation; dielectric heating (radio frequency and microwave heating) for drying; polymerisation; and powder coatings using infra-red ovens for curing instead of solvent-based coatings and conventional convection ovens (Eurelectric, 2004). Most often, converting a process to electricity improves process control and productivity. In many cases, electric-heating applications are more energy-efficient than their alternatives, especially at high temperatures. Optimal efficiency of an electric furnace can reach up to 95%, whilst the equivalent for a gas furnace is only 40% to 80%.

The use of electrochemical processes to produce iron ore, known as electro-winning, is currently in an early R&D phase. Aluminium is produced entirely by electro-winning and the approach is also used in the production of lead, copper, gold, silver, zinc, chromium, cobalt, manganese, and the rare-earth and alkali metals. If a technological breakthrough were to make the production of iron by electro-winning feasible, renewable energy could more easily substitute for fossil fuels in this major application.

Indeed the share of electricity in industrial energy consumption is expected to increase from one-fourth to one-third by 2050 (IEA, 2009*a*). The climate-friendly BLUE Map Scenarios are little different from the Baseline Scenario in this respect, with shares of electricity in industrial productivity variants shown as "high" (37%) or "low" (35%) (Figure 5.1).

Figure 5.1 **Electricity use by sector, as a share of final energy use**



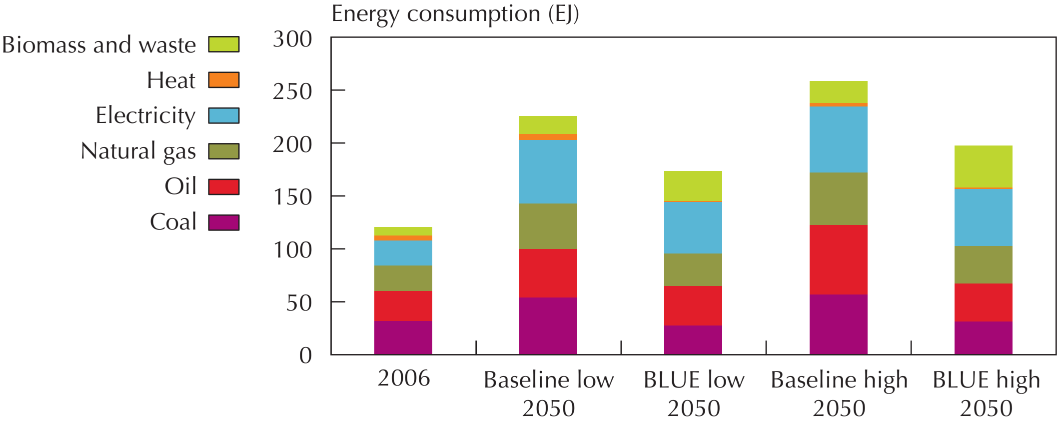
Source: IEA, 2009a.

Key point

The share of electricity in industry energy use is expected to rise to one-third by 2050.

The 2% difference may look small; however, it results from the fact that the BLUE Map Scenario includes greater energy efficiency improvements in the current uses of electricity in industry – the two larger areas being variable speed for most industrial electric motors, and better management of various "commodities" such as compressed air in networks. All in all, the use of fossil fuels is reduced in the BLUE Scenarios compared to the Baseline Scenarios, thanks to savings, substitution by electricity and by biomass and waste (Figure 5.2).

Figure 5.2 **Final energy use in industry, 2050**



Source: IEA, 2009a.

Key point

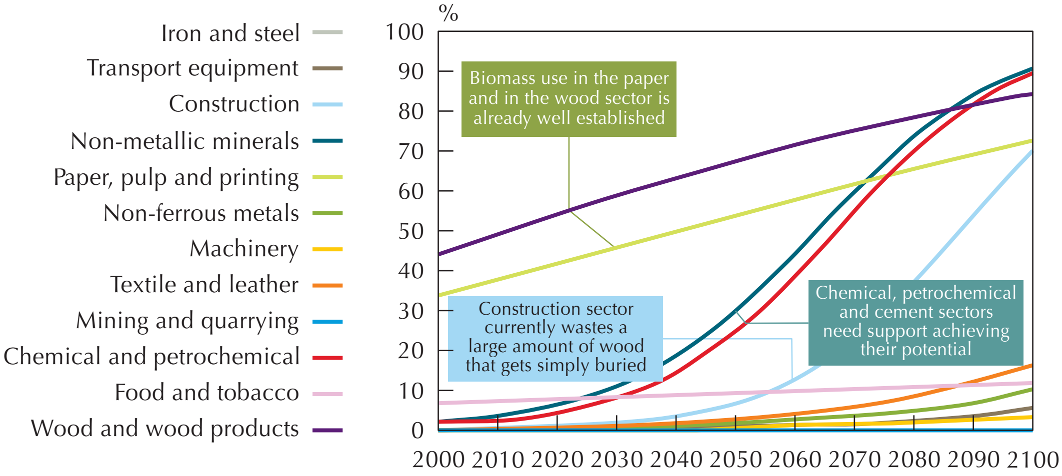
Fossil fuel use declines in the BLUE Scenarios, substituted by electricity and biomass.

Self-generation of electricity by industry may be driven by slightly different perspectives. In countries with good DNI, some industries are considering building their own concentrating solar power (CSP) plants to improve the security of the energy supply of their industrial facilities. One large cement producer is developing a project for a 40-MW CSP plant in Jordan, although this factory is already connected to the nationwide grid. Outages are frequent during peak loads, which tend to occur in the afternoon. The CSP plant, possibly with a few hours thermal storage capacity, would essentially reduce the demand on the grid from the cement plant during all peak and mid-peak times. The industry sector not only gets passively "solarised" as the electricity sector gets solarised – it can take part in this change. This is all the more true as industry offers numerous options for cogeneration, using not only electricity but large amounts of heat from either photovoltaic and thermal collectors or solar thermal electricity/concentrating solar power.

Biomass in industry

Biomass could slowly increase its share in a number of industry sectors (as solid biomass fuels such as "bio-coal" are further developed). Taibi and Gielen (2010) estimate the potential contribution of biomass in industry at 5 000 TWh per year by 2050 if there is no interregional trading of biomass; if interregional biomass trading takes place (notably from Africa to China), this contribution is estimated to be 8 000 TWh.

Figure 5.3 **Possible progression of biomass use in various industry sectors**



Biomass use in the paper and in the wood sector is already well established

Construction sector currently wastes a large amount of wood that gets simply buried

Chemical, petrochemical and cement sectors need support achieving their potential

Source: Taibi, Gielen and Bazilian, 2010.

Key point

Interregional biomass trading could increase its long term contribution to industry by 60%.

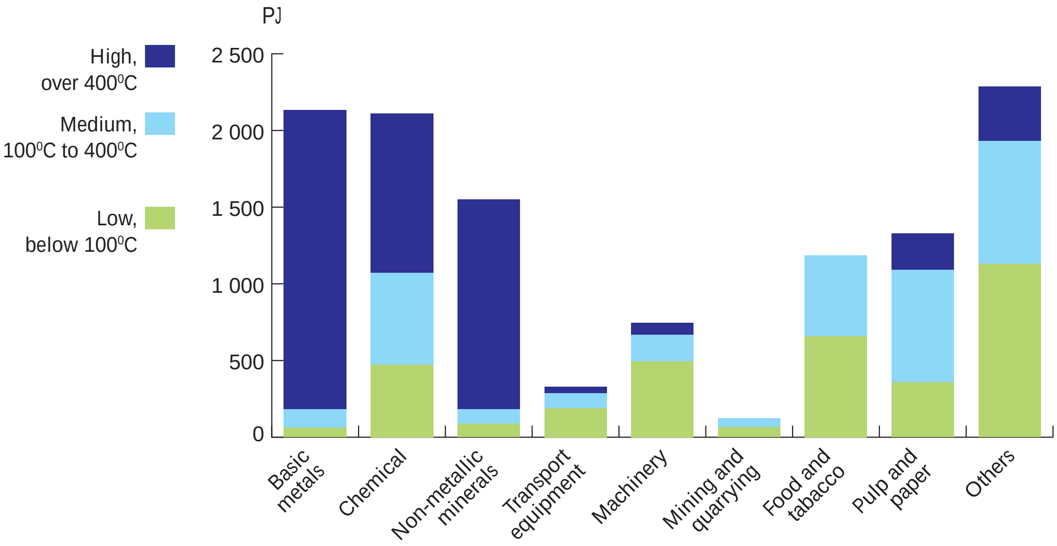
One option is to use charcoal, the original fuel for producing iron, in addition to or in lieu of electro-winning. Significant amounts of pig iron are still successfully produced using charcoal, notably in Brazil. For nearly 600 Mt of pig iron smelted annually in the early 2000s, about 250 Mha of tropical eucalyptus plantations would be needed, or about half Brazil's total forested area in 2000 (Smil, 2006).

But charcoal could be produced from a number of biomass sources, not only trees. Furthermore, the solid biomass to be used in industry, whether in the sectors identified by Taibi *et al.* or in other sectors, such as iron and steel, could be enhanced by using solar energy (apart from through photosynthesis). The transformation of biomass, in industry as well as for transportation, requires large amounts of energy, mostly heat, which is usually provided by burning part of the feedstock. Given possible limitations on the global biomass feedstock and its relatively high footprint, using solar heat at various temperature levels to process the raw biomass could possibly allow a further extension of its uses.

Solar heat

Process heat is the major energy consumer in the energy sector. Figure 5.4 illustrates the repartition of industrial heat demand in greater Europe (32 countries) by temperature bands and by industry branches. Low-temperature heat is 30%, high-temperature heat 43% and medium-temperature heat 27%. Other studies suggest that about two-thirds of the heat in the 100°C to 400°C range is used in industry at temperature levels lower than 200°C.

Figure 5.4 **Estimated industrial heat demand by temperature range in Europe, 2003**



Source: Werner, 2005-2006.

Key point

More than half process heat is of low and medium temperatures.

Other studies performed in various countries differentiate low- and medium-temperature heat as above and below 160°C for selected industry sectors. This is very helpful for a low-carbon process, as process heat below 160°C can be provided by solar thermal collectors in most cases, though the cost-effectiveness obviously depends on the global (direct and diffuse) solar resource. The most significant current application areas are in the food and beverage industries, the textile and chemical industries and for simple cleaning processes (*e.g.* car washes, as on Photo 5.1) where simple collectors can provide the desired 50°C to 90°C temperature. In some cases a number of uses are combined: the Hammerer transport company in Austria uses solar hot water to clean transport containers as well as for space heating of its offices.

Photo 5.1 **Solar water heaters can be used in service areas**

Source: AEE INTEC.

Key point

Stationary solar thermal collectors provide low-temperature process heat.

Cleaning is a process that occurs in many forms. Cleaning of bottles, cans, kegs and process equipment is the most energy-consuming part in the food industry. Metal treatment plants (*e.g.* galvanizing, anodizing and painting) have cleaning processes for parts and surfaces. The textile industry and laundries clean fabrics; service stations clean cars. All of them need warm water at temperatures below 100°C and even below 60°C, so they provide an excellent application for solar thermal energy. Storage and the integration into the existing heat supply system is rather easy in these cases since very often storage tanks already exist and water is the main medium.

Most of the washing processes require subsequent drying, which is also very energy intensive. Although the drying medium will be warm air in general, it can be heated up through water/air – heat exchangers. Preheating with solar heat might be a viable option in that case. Solar air collectors represent another option, which has been particularly developed in India for crop drying, food processing and textile manufacturing sectors (Photo 5.2). Crop drying is an effective alternative to cooling for conservation, particularly in a country where large quantities of crops are lost through lack of conservation techniques.

Photo 5.2 **Passive solar dryer for coffee beans in Costa Rica**

Source: Solar Wall.

Key point

Solar air drying helps preserve crops where refrigeration is lacking.

Evaporation is a form of drying and both involve a volatile component changing phase through the input of energy. Applications can mainly be found in the food industry and chemical industries.

Pasteurisation and sterilisation need heat of 75°C and 105°C respectively. In food industry and biochemistry there are numerous applications. With liquids, pasteurisation can be performed in heat exchangers, but for solids (cans or jars), a heat-transfer medium such as water, air or steam is required.

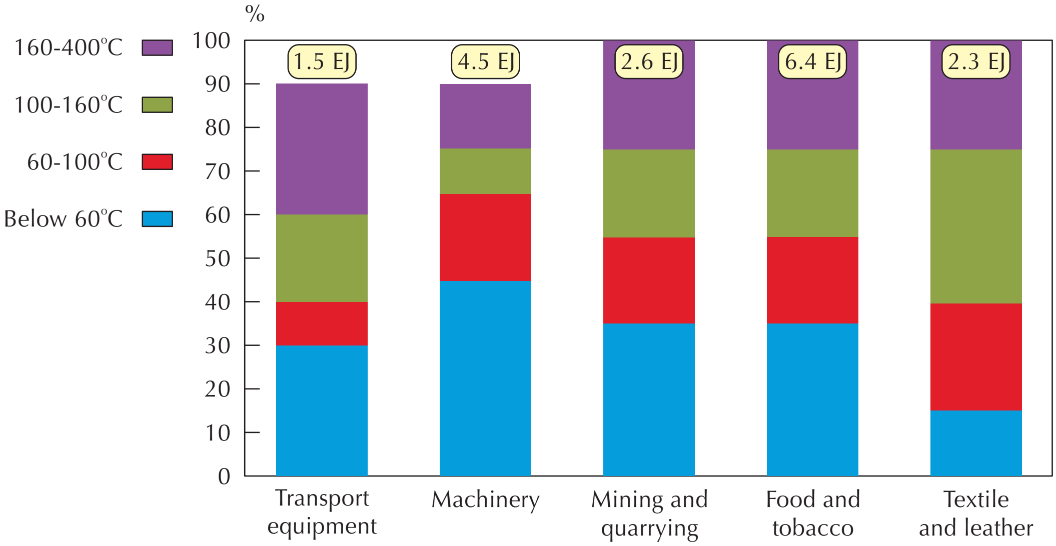
Preheating boiler feed water is another possible application for solar heat in the process industry. Since this is a low-temperature heat sink, solar energy is suited very well, but there might be other, less costly heat sources available for this process.

Heating of production halls is necessary in many countries in wintertime. Although heating is not purely an industrial application, special challenges might arise from using the heat supply system for both processes and space heating.

Solar cooling with absorption systems is a very special application of solar heat in industry. Integrated into the whole energy system of the industrial plant, it might offer special opportunities in the food industry, for instance.

Most of the process heat in the medium range from 100°C to 200°C is used in the food, textile and chemical industries for such diverse applications as drying, cooking, cleaning, extraction and many others (Figure 5.5). Good efficiency in collecting heat requires slightly more sophisticated collectors, such as advanced flat-plates or evacuated tubes possibly complemented with small CPC devices (see Chapter 7). Recent improvements in the technology of stationary collectors suggest that the cost-effectiveness could be roughly similar in a 50°C to 160°C temperature range, as greater investment costs will also lead to greater fuel savings.

Figure 5.5 **Process heat in selected sectors, by temperature levels**



Source: Taibi, Gielen and Bazilian, 2010.

Key point

Food, beverage, textile and transport industries need mostly low to medium-temperature heat.

Many industrial parks are located outside cities and surrounded by flat agricultural land. It could be possible to reconvert some limited agricultural lands to an energy use. Waste lands and brown fields (contaminated sites) offer even more preferable options.

High-temperature process heat is different. In areas with good DNI, solar heat can be provided at any temperature level, with concentrating solar systems (see Chapter 7), use of which has been suggested for many industrial processes, from forming processes to thermal treatment of crude oil. Parabolic troughs have been the most widely used devices for industrial process heat below 400°C, mostly for food or textile industries. For example, the Frito-Lay factory in Modesto, California, uses 5 065 m^2 of parabolic troughs on 1.5 ha to deliver pressurised water at 250°C. The steam generated heats the oil used to fry potato and corn chips. In India, a few laundries are being equipped with several Scheffler dishes, hooked up with existing boilers, to provide steam for washing and cleaning. In Egypt, a pharmaceutical company some time ago installed parabolic troughs to produce the bulk of its process heat.

Another example is pottery firing with the solar oven of Mont-Louis (France) with Moroccan potters (Chapter 7), which substitute for hardly sustainable biomass. There are about 30 000 pottery kilns in Morocco, requiring significant amounts of fuel wood; this has led to some desertification, as the resource is scarce. Moreover, ash regularly destroys up to one-third of the pottery produced. Clean cooking in a solar oven would significantly improve production, reduce costs and help preserve the environment. Experiments at Mont-Louis have also shown that even mid-size solar ovens can easily be used to produce ceramics, glass, as well as aluminium, bronze and other metals.

The lack of combustion residues is an interesting feature of solar ovens. At high temperatures, concentrated solar energy can also be used for driving the endothermic reaction that produces lime (calcination reaction). Running this reaction at above 1 000° C would reduce emissions of the process by 20% to 40%, depending on the manufacturing plant. It would also produce very high purity lime for use in chemical and pharmaceutical sectors.

Taibi and Gielen (2010) set the potential for solar heat in the industry by 2050 from 1 550TWh$_{th}$/y to 2 220 TWh$_{th}$/y. Almost half of this is projected to be used in the food sector, with a roughly equal regional distribution between OECD countries, China and the rest of the world, mainly in Latin America (15%) and Other Asia (13%). Costs depend heavily on radiation intensity, but are expected to drop by more than 60%, mainly as a result of learning effects, from a range of USD 61/MWh$_{th}$ to USD 122/MWh$_{th}$ in 2007 to USD 22/MWh$_{th}$ to USD 44/MWh$_{th}$ in 2050.

This estimate for solar heat may seem low, at less than 5% of a total estimated consumption of almost 50 000 TWh/y for the global industry by 2050. The profitability of solar process heat is likely to be significantly greater than that of direct solar space heating given that the demand is, in most cases, roughly constant throughout the year. The case is much closer to solar water heaters or solar-assisted district heating than to space heating. Difficulties and competitors, however, should not be underestimated. For example, the pulp and paper industry meets its large steam needs by using biomass, *i.e* by-products of the wood preparation and virgin pulping processes.

Heat pumps, whether closed-circuit pumps, mechanical vapour compressors, or scarcer absorption heat pumps and heat transformers, operate in the same temperature range as non-concentrating solar thermal collectors. They might be preferred in some cases, for several reasons, such as low solar resource, lack of available space for collectors, or greater flexibility in being re-used or resold if the industrial process evolves. In many industry sectors (for example in the glass industry) the low-temperature heat being used is waste heat from higher-temperature processes (run by natural gas in most cases), with or without a temperature lift provided by heat pumps. Solar heat cannot compete in not-so-sunny places where it cannot also provide the high-temperature heat.

Fossil fuels are chosen for various industrial processes not only because they provide energy – they also provide feedstock or are part of the processes. More than one-half of the energy used in the bulk chemicals industry is for feedstock purposes. Fly ash resulting from the combustion of coal plays a role in the production of cement, which is why coal is the main fuel used in this sector, with various wastes eliminated by the high-temperature level – 1 450°C – of the kilns. Similarly, carbon is used as reducing agent for iron ores in blast furnaces in the process of making steel.

Petroleum refining is a highly energy-intensive process, in which crude oil and intermediate streams are subjected to high pressure and temperature. The processing of crude oil results in a significant amount of so-called "still gas", which is recovered and burnt. Machines are powered by electricity, often cogenerated with steam in the refinery. In 2000, purchased natural gas accounted for 28%, and purchased electricity for only 4%, of the needs of the refineries. The availability of still gas restricts the possible role of renewables in refining petroleum.

Hydrogen used for synthesis of fertilisers and cleaning petroleum products could be produced either from water electrolysis using excess wind or PV power, or from steam reforming of natural gas. In this case, it would use concentrated solar heat as the energy source, instead of burning natural gas (on top of the "still gas" produced in the refineries themselves). Preliminary indications suggest that the second option would be three to four times less costly but is only available where high DNI permits. Solar heating of the water could, however, be used extensively to reduce the amount of electricity required by electrolysis. Apart from a few direct industrial uses of hydrogen, solar hydrogen could be mixed in various proportions with methane, transported as such and ultimately burnt in combination with natural gas.

Desalination

Arid regions are both blessed by good DNI resources and cursed by water shortages. Desalination techniques are expected to continue expanding, particularly in the Middle East. Two main techniques exist: distillation and reverse osmosis. Distillation requires large amounts of thermal energy, while reverse osmosis consumes large amounts of electricity. It is tempting to think that CSP plants, which generate electricity from heat, could have an important advantage in combination with multi-effect desalination plants in "cogenerating" electricity and the heat needed for the desalination process.

A closer examination, however, suggests that such an advantage does not exist. The diversion of low-pressure, low-temperature steam from the turbine to serve the distillation plant would reduce the electricity generation. Coastal areas often enjoy lower DNI than more inward sites. The choice of desalination process may primarily depend on the salinity of the marine or brine waters. More saline waters increase the electricity loads of reverse osmosis plants and may lead to a preference for distillation plants, while less saline waters may lead to a preference for reverse osmosis technologies run on solar electricity from concentrating solar power plants.

If this sort of "cogeneration" exists, it should paradoxically be sought for in the combination of CPV systems and distillation plants. CPV systems may need or benefit from cooling, and the heat removed by this cooling process may serve the purpose of distillation while increasing, even slightly, the efficiency of the solar plant, not reducing its electric output.

In any case, however, the co-existence of fresh water shortages and excellent direct solar resource certainly offers many opportunities for this growing industry sector to be powered by solar, whether heat or electricity.

Similarly, the potential for water detoxification by solar light is important in sunny developing countries and to some extent already mobilised in conventional open-air wastewater treatment plants. It can contribute to provide clean water to people and combat water-related diseases in the developing world. Research and development in this area is part of the scope of the IEA SolarPACES programme.

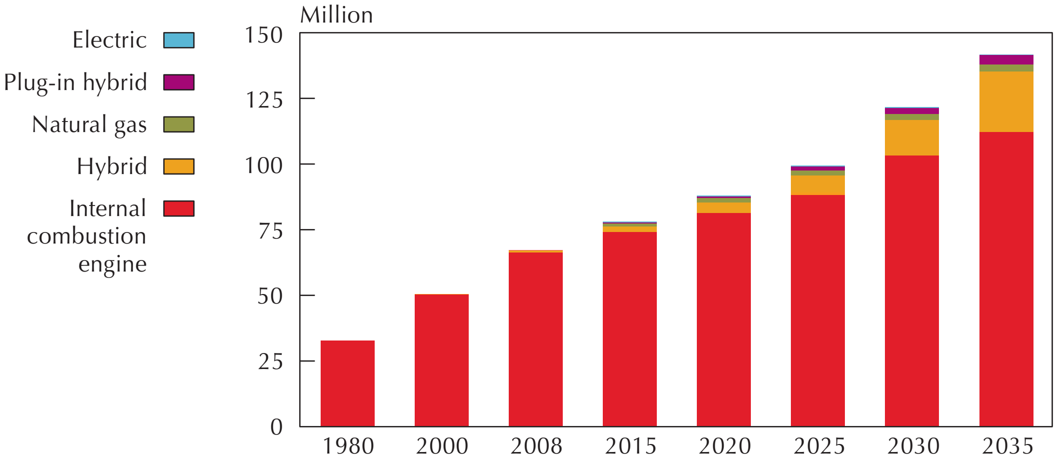
Transport

Even more than for industry, biomass and electrification would be the major vectors for introducing large-scale renewable energy – and solar energy in particular - into the transport sector. If used as an external energy source for processing the raw biomass to transport fuels, solar could also increase the conversion efficiency and thus the available amount of liquid biofuels. There seems to be little opportunity for direct solar use in the transport sector, although the emergence of solar fuels may change the picture in the longer term.

Although electricity's current share of transport fuel across all modes is between 1% and 2% worldwide, its effective role in the transport of goods and people is significantly greater. It runs most passenger or freight trains, tramways, trolleys and underground transport systems around the world, not to mention elevators, which offer transport services in dense cities. The discrepancy is due to the much higher energy efficiency of mass transit over individual transport systems, and of rail-based over road-based freight systems. This adds to the greater efficiency of electric systems *versus* fossil fuel systems at end-use level; for example, for individual transport in light-duty vehicles, 1 kWh of electricity replaces about 3 kWh of petroleum products.

The IEA scenarios project an impressive growth in the number of light-duty vehicles in the world in the coming decades and in the related energy consumption and CO_2 emissions, despite energy efficiency improvements. In the *WEO 2010* "New Policy Scenario", roughly compatible with the countries' pledges made in Copenhagen at the UN Conference on Climate Change, sales of electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV, combining an internal combustion engine with electric traction and batteries) do not prevent a steep increase in the global fleet of conventional cars with internal combustion engines (Figure 5.6).

Figure 5.6 **Passenger light-duty vehicle sales by type in the New Policies Scenario**



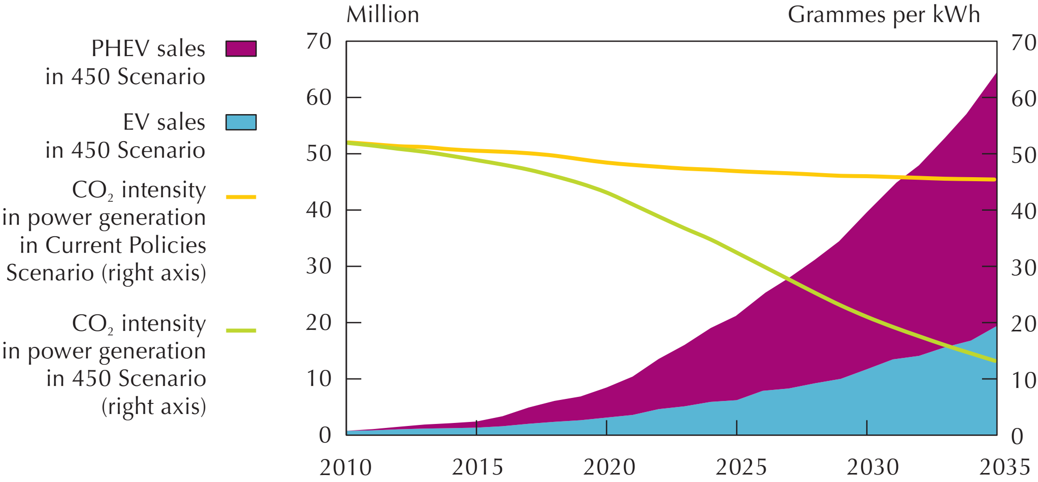
*Source: IEA analysis based on IEA, 2010*b.

Key point

The global fleet of light-duty vehicles with internal combustion engines will continue to grow.

The 450 Scenario of *WEO 2010* foresees EVs and PHEVs taking off more rapidly this decade and reaching 39% of new sales by 2035, making a significant contribution to emissions abatement, reflecting a major decarbonisation of the power sector (Figure 5.7).

Figure 5.7 **Sales of plug-in hybrid and electric vehicles in the 450 Scenario and CO_2 intensity of the power sector**



*Source: IEA analysis based on IEA, 2010*b.

Key point

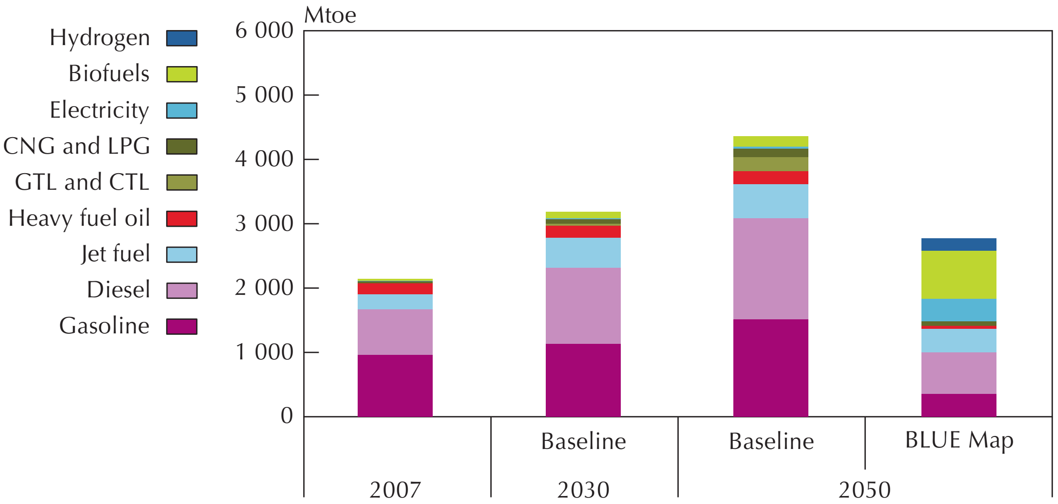
In the 450 Scenario, EV and PHEV expand rapidly while electricity is decarbonised.

In the BLUE Map Scenario, which looks farther into the future, EV and PHEV sales are each projected to reach about 50 million by 2050, with combined stocks of over 1 billion such vehicles on the road in that year. In the BLUE EV Scenario, the stock of EVs and PHEVs is even greater.

The evolution of energy use by fuel types to 2050 in the Baseline and BLUE Map Scenarios, with several variants, of *ETP 2008* is shown in Figure 5.8. A mix of energy efficiency improvements, modal shifts (especially in the BLUE Map/Shifts variants), use of biofuels and deployment of EVs, would bring fossil fuel use down not only from Baseline levels by 2050, but even from current levels. This projection also integrates fuel-cell vehicles (FCVs) fuelled by hydrogen from a variety of non-carbon sources.

Direct uses of solar energy in transport are currently purely symbolic, illustrated by solar planes, boats and cars (see Photo 5.3, Photo 5.4 and Photo 5.5). Beyond the symbols, direct solar contributions could be made by using PV systems to save fuel, thereby reducing the consumption of fuel going towards the production of on-board electricity for general purposes. One possible advantage would be to maintain some air-conditioning when the car is stationary under sunshine. On lighter vehicles, PV systems can extend the range by 15 km, which in some cases could represent an entire extra day's use.

Figure 5.8 **Evolution of energy use by fuel type in transport worldwide**



Source: IEA, 2010a.

Key point

Fossil fuel use in transport could be cut by half compared to Baseline in 2050.

Most vehicles' high intensity of energy consumption will prevent solar energy from making a large contribution. However, vehicles could be seen as remote sites, disconnected from the grid on the go and in other situations, which are electrified with a relatively inefficient generation system using a fuel that is, at least in several countries, heavily taxed, so integrated PV systems might make a useful contribution.

Road transport represents by far the largest share of energy consumption in transport. The extent to which road transport systems can be electrified is an important question. With rapid battery exchanges, one may suppose that at some point in the future most cars would be EVs or PHEVs. PHEVs can run on electricity mode for daily commuting, while permitting use of liquid fuels for longer trips. Evens EVs could travel long distances if a rapid effective battery-exchange service is developed, which could resemble the way tired stage horses were exchanged for fresh ones in the past. Issues relating to the ownership or age of batteries could presumably be solved in a world of electronic transactions, as they were solved in the Middle Ages with less sophisticated communications. For example, in Israel the "Better Place" project plans to lease batteries rather than sell them and charge customers by the distance travelled rather than by the amount of electricity consumed.

Trucking is often considered impossible to electrify – except for the consumption of amenities (*e.g.* cooling) when idling. Hybridisation of the trucking fleet, however, could offer additional options.

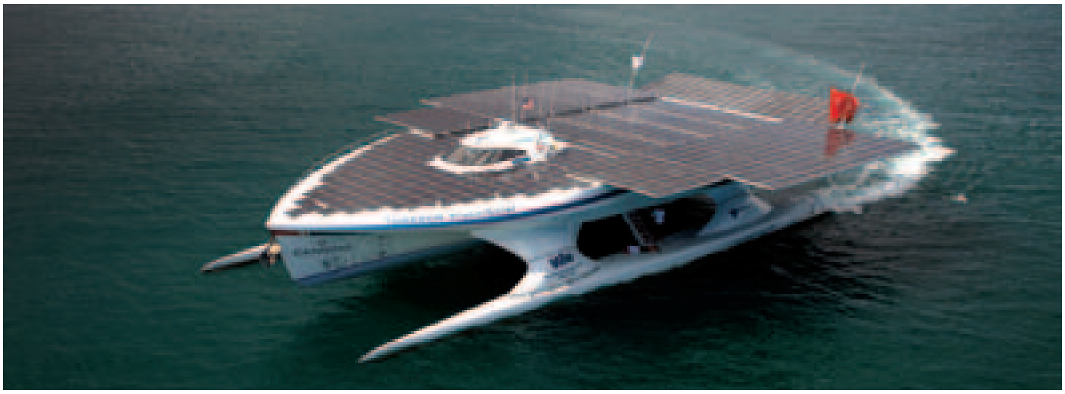
On short trips, hybridisation would improve efficiency significantly, as loads and speeds often vary. On long trips, of 800-kilometre distance and above, mode switching could be encouraged – including transporting containers on specific trains on new dedicated railways. For middle distances, trucks could be fed with electricity through induction or from overhead wires through trolley poles while on the road – specifically, on highways. In Europe, almost half the total tonne-kilometres are in these middle-distance trips (500km), with an always significant share of these distances run on highways. The potential thus represents more than 40% of oil consumption and CO_2 emissions of current road freight – depending on the share of trips over 500 km long that can actually be transferred to rail.

Full electrification of the transport sector seems out of reach. Even if long-haul trucking can be electrified, it seems impossible to electrify shipping and, above all, aviation. Some amounts of biofuels or fossil fuels may need to be burnt in PHEVs, and even in EVs – vehicles entirely moved by electricity – to produce heat. In transport using fossil fuel, most of the energy in a vehicle is wasted as heat, so heating the vehicle's interior and providing passenger comfort is easy. With electric vehicles there is no waste heat. In winter, heating the cars' interior may halve the range of some vehicles. Burning liquid fuels for heating the car, with a much better efficiency than in the engine, could be a solution although carmakers fear that this may dissuade potential clients. It is likely too that no attention has been paid thus far to cars' thermal performance, as so much wasted heat was available for free.

Photo 5.3 **The experimental PV-run plane Solar Impulse flew for 26 hours**

Source: First flight © Solar Impulse/Reuters/Christian Hartmann/Pool.

Photo 5.4 **This 31-m demonstration boat is circumnavigating the globe, powered only by its PV panels**



Source: TURANOR © PlanetSolar.

Photo 5.5 **PV roof on a plug-in hybrid**

Source: Kia Motors America, Inc.

Key point

Vehicles offer surfaces to sunrays that can be used for small electricity generation.

Hydrogen could be another possible vector for introducing solar energy in road transportation. Liquid fuels made from hydrogen would be an option, offering greater climate change mitigation potential over unconventional oil with higher associated upstream emissions, and even more over coal-to-liquid fuels, which entail very high upstream CO_2 emissions unless these are captured and stored (see Chapter 9). But as such fuels would contain carbon atoms they would offer only limited emission reductions over kerosene and other petroleum products from conventional oil.

The use of hydrogen energy chains from renewable electricity could give vehicles greater range, but with significantly lower energy efficiencies along the chains and, at present, much higher costs. Carmakers maintain, however, that fuel cell cars could cost ten times less than today by 2020 (BMW AG *et al.*, 2011). If this reduction is achieved, fuel cell cars will offer another means of decarbonising road transport. If renewable electricity is the source of hydrogen, however, it should be considered a variant of electrification, not a means to further reduce the consumption of petroleum products and associated CO_2 emissions. The outcome would be different if the source is a concentrating solar process directly producing hydrogen (as described in Chapter 9). Solar hydrogen might be used more conveniently when blended with natural gas, as in gas-fired power plants.

Aviation and marine transportation have good prospects for energy efficiency improvements, but limited options for switching away from fossil fuels, beyond biofuels and solar fuels. PV can provide small fuel savings, as most new cargo ships include on-board electricity generation and electric propellers. Wind power, with automatic sails or kites, could save more significant amounts of fuels in certain applications. Unmanned planes, however, could sustain very long aerial watching missions at low speed thanks to PV cells – an emerging niche market that recalls the pioneer role of PV in satellites. Global positioning systems, telecom satellites, earth observation systems and long space missions are possible only thanks to PV cells, which already benefit billions of people.

Solar hydrogen, in liquefied form, could find its best application in aviation. Reservoirs for compressed hydrogen would be too heavy for aviation. Spherical or cylindrical reservoirs for liquid hydrogen weigh much less. The usual problem with liquid hydrogen is the "boiling-off" that makes some gas continuously leak from the reservoir. On top of environmental issues associated with those leaks, this is not convenient for road transport, but could be acceptable for planes that are fuelled immediately before departure at all world airports. The Cryoplane study (Faaß, 2001) has shown that the greater volume of H_2 as a fuel could also be acceptable in specifically designed aeroplanes.

Policies

Policies to support the deployment of direct solar heat in industry currently represent a very significant missing element of renewable energy policies in almost all countries. Solar heat is likely to be closer to competitiveness in the industry sector than for space heating in buildings, because the need is more constant throughout the year and does not reach its lowest point when the resource is at its peak. Scarce public money could thus be spent very effectively in boosting solar output. Such investment would also encourage the development of solar heat and reduce its costs, which would ultimately benefit other uses of solar heat. Policies to support solar heating and cooling will be considered in more detail in the forthcoming IEA Technology roadmap for solar heating and cooling, to be published in 2012.

Solar energy generation by industry must also be encouraged. Governments and grid operators, especially in countries with weak grids and frequent electricity shortages, need to react appropriately to energy-intensive industries generating their own solar electricity to secure their own supply and guarantee their processes and equipment against the risks of shortages. Negotiations on electricity trade with electricity self-producers should acknowledge that more secure supply for the grid is a welcome by-product, not the primary aim of such developments.

In both industry and transport sectors, an integrated approach to the deployment of solar energy would aim to accelerate the deployment of many enabling technologies. In particular, it would seek to accelerate the deployment of efficient electric processes to replace fossil fuels.

The full treatment of all relevant technologies and policies would go beyond the scope of the present publication, but has been addressed in many IEA publications (IEA, 2009*a*, IEA, 2009*b*, IEA, 2010*a*) and specific Technology Roadmaps (IEA, 2009*c*; IEA, 2011*e*; IEA, 2011*g*) and will undoubtedly remain the focus of further analytical work by the IEA.

PART B
TECHNOLOGIES

Chapter 6
Solar photovoltaics

The photovoltaic (PV) technology has been known for many years but its large-scale use began only in the last few years, with impressive growth rates. Global installed capacity went from 5 GW in 2005 to 40 GW in 2010. Costs went down rapidly, and will continue to do so in all likelihood. PV electricity, already competitive in remote sites, will start to compete for distributed on-grid electricity generation at peak demand times in various regions of the world during this decade.

Background

In 1839, the French physicist Edmond Becquerel discovered the photoelectric effect, on which photovoltaic technology is based. The effect was explained in 1905 by a then obscure assistant examiner of the Swiss Patent Office, Albert Einstein, who received a Nobel Prize for it in 1921. The first patents for solar cells were filed in the 1920s by Walter Snelling and Walter Schottky. In 1954, Darryl Chapin, Calvin Fuller and Gerald Pearson, associates of Bell Labs, invented the silicon solar cell for powering satellite applications – an extreme example of remote, off-grid electricity demand. In the early 1970s, PV was adapted to terrestrial applications by Elliot Berman.

Thin films appeared in 1986. Considerable progress has since been made in the manufacturing process, efficiency and longevity of the various families of thin films.

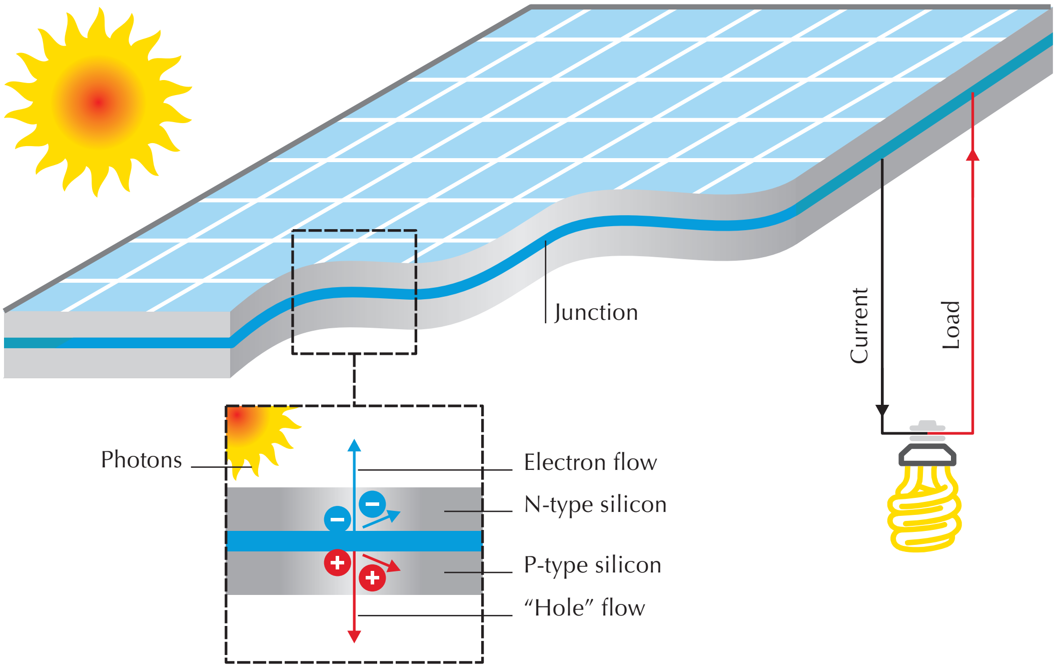
The PV learning curve

Photovoltaic (PV) cells are semiconductor devices that enable photons to "knock" electrons out of a molecular lattice, leaving a freed electron and "hole" pair which diffuse in an electric field to separate contacts, generating direct current (DC) electricity (Figure 6.1). Photovoltaic cells are interconnected to form PV modules with a power capacity of up to several hundred watts. Photovoltaic modules are then combined to form PV systems.

Photovoltaic systems can be used for on-grid and off-grid applications. Individual PV cells are assembled into modules, several of which can be linked together to provide power in a range of from a few watts to tens or hundreds of megawatts. Off-grid systems may or may not require an electricity storage device such as a battery for back-up power. Some applications, such as solar powered irrigation systems, typically include water reservoirs.

PV systems usually require an inverter, which transforms the direct current (DC) of the PV modules into alternate current (AC), most usages being run on AC. Grid-tied systems similarly require one or several inverters to inject their electrical output into the mains. The components associated with this delivery process, such as inverters, transformers, electrical protection devices, wiring, and monitoring equipment, are all considered part of the "balance of system" (BOS). In addition, the BOS includes structural components for installing PV modules, such as fixed mounting frames and sun-tracking systems (if any).

Figure 6.1 **The photovoltaic effect**



Source: EPIA, 2011.

Key point

Photovoltaic systems directly convert light into electricity.

PV cells, modules and systems have an excellent track record of progressive cost reductions, with a learning rate of about 20% for modules, and about 12.5% for systems. This means that each doubling of the cumulative installed capacity has led to a cost reduction for modules of about 20%.[1] The historical learning rate for PV modules was actually 22.8% per year on average over 1976-2003.

Three major factors driving cost reductions from 1980 to 2001 have been identified: manufacturing plant size, module efficiency and purified silicon cost. The driving role of scaling-up in cost reduction is also demonstrated by the success of some new entrants, which were able to raise capital and take on the risk of large investments but offered no technical superiority. Ten out of the 16 major advances in module efficiency can be traced back to government and university research and development programmes, while the other six were accomplished in companies manufacturing PV cells. Finally, reductions in the cost of purified silicon were a spill-over benefit from manufacturing improvements in the microprocessor industry (Nemet, 2006).

From 2004 to 2007, however, a bottleneck in the production of purified silicon led to a steep increase in its cost (Figure 6.2), resulting in a slight increase in PV costs, seemingly a violation of the learning curve concept.

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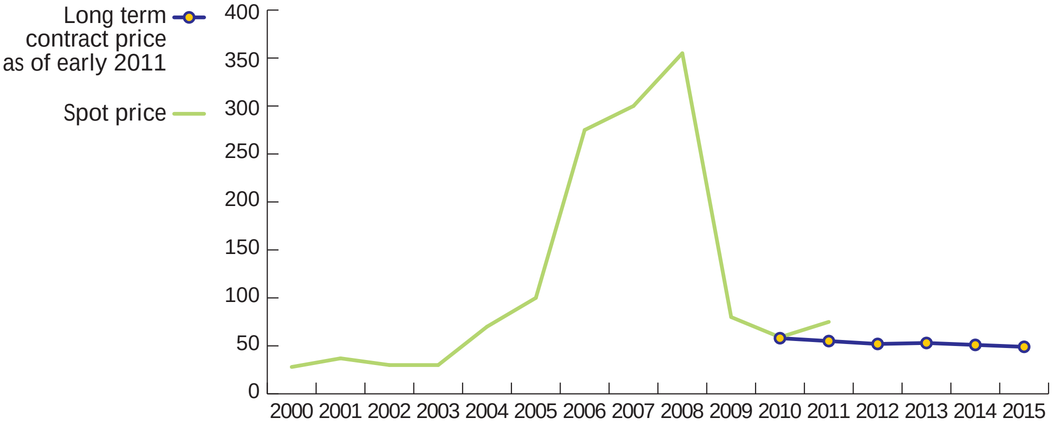
[1] *Progress ratio is another way of expressing the same reality and is calculated at 1 minus the learning rate, or about 80% in this case (the lower the progress ratio, the faster the progress).*

Figure 6.2 **Polysilicon spot and weighted average forward contract prices (USD/Kg)**



Source: Bloomberg New Energy Finance.

Key point

A shortage of purified silicon stopped PV cost reductions from 2004 to 2007.

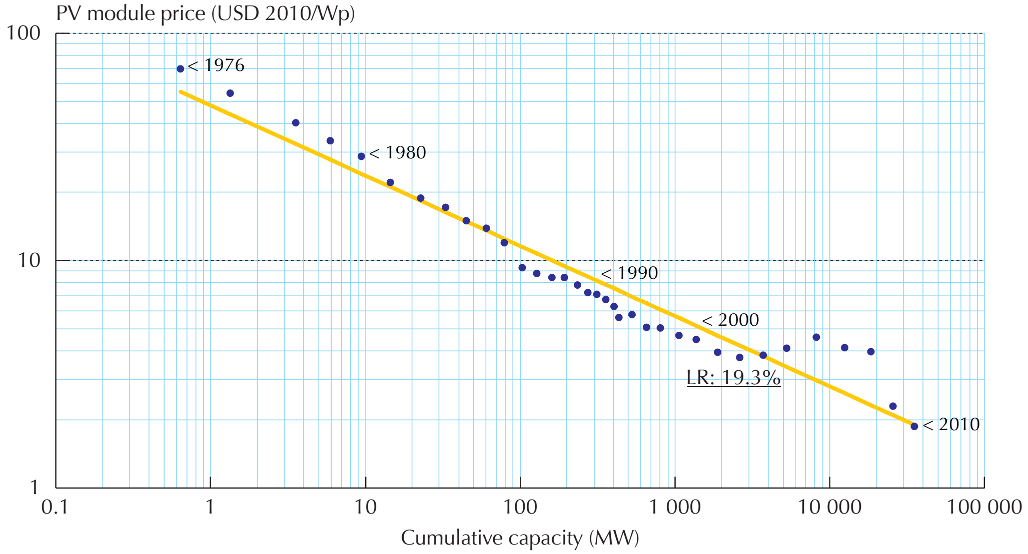
Since then, costs fell by 40% in only two years – 2008 and 2009 – and PV costs went back to the previous track corresponding to a learning rate of 19.3% over 34 years (1976 to 2010) (Figure 6.3). Currently, the lowest manufacturing cost of PV modules is USD 0.74 per watt-peak (USD/W_p – a measure of the nominal power of a PV device), achieved by the cadmium-telluride (CdTe) PV company *First Solar*, bringing the cost of large-scale systems around USD 2/W_p. Silicon PV modules are about USD 1.80/W_p, and single-crystalline silicon (sc-Si) utility-scale systems at USD 3.00/W_p.

The PV learning rate is the highest ever seen in the energy world. By contrast, on the basis of past experience, the *WEO 2010* assumes, for decades to come, learning rates of 1% for hydro power, 5% for biomass and geothermal, 7% for wind onshore, 9% for wind offshore, 10% for CSP, 14% for marine energy, and 17% for PV. The rapid learning with PV probably arises from the fact that PV technologies are a spinoff from semi-conductor technologies. Even higher learning rates have been recorded for other semi-conductor based technologies: 45% for dynamic random-access memory (DRAM) chips, 35% for flat panel displays. Very steep learning curves for electronic devices are based on the integration density of transistors. Except for cooling needs, there is no reason to have large surface areas, contrary to displays and PV cells, which may explain the less rapid cost reductions in their cases.

State of the art and areas for improvement

The various photovoltaic technologies are at differing levels of maturity – and all have a significant potential for improvement. Increased and sustained research, development and demonstration (RD&D) efforts are needed over the long term in order to accelerate cost reductions and the transfer to industry of the current mainstream technologies, to develop and improve medium-term cell and system technologies, and to design novel concepts and bring them to industrial use.

Figure 6.3 **The PV learning curve**



Source: Breyer and Gerlach, 2010.

Key point

PV has shown a learning curve of 19.3% on average over 34 years.

Crystalline silicon

Current commercial PV technologies are wafer-based crystalline silicon (c-Si) and thin films (see next section). Crystalline silicon technologies – single-crystalline (sc-Si) or multi-crystalline (mc-Si) – currently dominate the market with an 85% share. Cells are sliced from ingots or castings, or made from grown ribbons, of highly purified silicon. A potential junction is created, an anti-reflective coating deposited and metal contacts added. The cells are then grouped into modules with a transparent glass for the front, a weatherproof material (usually a thin polymer) for the back, and often a frame around. The back can also be made of glass to allow light through.

Modules are usually guaranteed for a life-time of 25 to 30 years at minimum 80% of the rated output. Sc-Si cells show efficiencies – the ratio of electric output over the incoming solar energy – of 14% to 22%, mc-Si from 12% to 19%. These efficiency levels are usually given in "standard" conditions, including air mass of 1.5 (distance travelled through the atmosphere 50% greater than when the sun is exactly overhead) and 25°C external temperature. But the efficiency of crystalline silicon PV decreases with rising temperature levels. Crystalline module efficiencies are slightly lower than cell efficiencies. Advanced manufacturing technologies, such as buried contacts, back contact cells, texturing processes and sandwiches of crystalline and thin films promise increases in efficiency.

Although c-Si cells represent the most mature PV technology, there is still room for improvement. Important aims are to further reduce the thickness of cells to bring the use of costly highly-purified silicon significantly below 5 g/W; to reduce the energy and labour costs of the manufacturing processes; to increase the efficiency and lifetime of the cells; and to reduce other system costs. Of particular concern is the use of silver, the price of which doubled in the past year, and now represents about 5% of module prices. PV already represents about 10% of the global demand of this precious metal.

Thin films

Thin films are made from semi-conductors deposited in thin layers on a low-cost backing. There are four main thin-film categories:

- amorphous (a-Si) with efficiencies from 4% to 8%;
- multi-junction thin silicon films (a-Si/ μc-Si), made of an a-Si cell with additional layers of a-Si and micro-crystalline silicon (μc-Si) with efficiencies up to 10%;
- cadmium-telluride (CdTe) with efficiency of 11%; and
- copper-indium-(di)selenide (CIS) and copper-indium-gallium-(di)selenide (CIGS), with efficiencies from 7% to 12%.

Thin film manufacturing has been highly automated, and some use roll-to-roll printing machines, driving costs down. Thin films now offer life-time almost similar to those of the crystalline silicon wafer. Lower efficiencies of thin films *versus* crystalline silicon modules means that a greater surface area is needed to produce the same electrical output; however the ratio of kWh over kW of peak capacity (kWp) depends only on the solar resource. One advantage of non silicon-based thin films, important in hot climates, is that their efficiency does not decrease with temperature levels, or decreases much less than that of silicon PV cells.

The use of cadmium, a poison and environmental hazard, in thin films often raises concerns. However, cadmium residue from the manufacturing process is recovered, and studies show that CdTe in glass-glass modules would not be released during fires. Recycling of CdTe thin films is operational and allows recovery of 95% of cadmium and tellurium. CdTe films use cadmium 2500 times more efficiently than Nickel-Cadmium (Ni-Cd) batteries in delivering electricity. In sum, the life-cycle cadmium emissions from the use of CdTe PV modules are about 0.2 μg/kWh to 0.9 μg/kWh and mostly result from the electricity used in the process when it is produced by burning coal, which itself entails Cd life-cycle emissions of about 3.1 μg/kWh (Fthenakis, 2004).

Thin film "modules" can be made flexible and offer a great diversity of sizes, shapes and colours – especially CIGS thin films. This helps in developing specific applications for integration into the envelopes of buildings, going from building-adapted PV (BAPV) to building-integrated PV (BIPV).

Hybrid PV-thermal panels

To maximise the energy efficiency per surface area of receiving panels, manufacturers now offer hybrid systems, which collect electricity from the PV effect and heat simultaneously, thereby adding the efficiency of PV to that of heat collectors, reaching a cogeneration efficiency of 80% or more. While this combination was initially developed with air collectors, it is now available with water collectors as well (Photo 6.1). Non-covered PV-thermal (PV-T) collectors consist of heat pipes on the back of PV modules. Covered PV-T collectors consist of PV modules placed inside flat-plate solar heat collectors. The non-covered PV-T collectors increase the electricity output, while the low-temperature heat collected can be used in combination with heat pumps. Covered PV-T collectors replace PV modules and heat collectors, slightly decreasing the electric efficiency but significantly increasing the total solar energy yield of a roof surface compared to side-by-side installations (Dupeyrat *et al.*, 2011). Solar air heaters too can be combined with PV.

Photo 6.1 **PV-thermal collectors manufactured in Turkey**

Source: Solimpeks Solar Energy Corp.

Key point

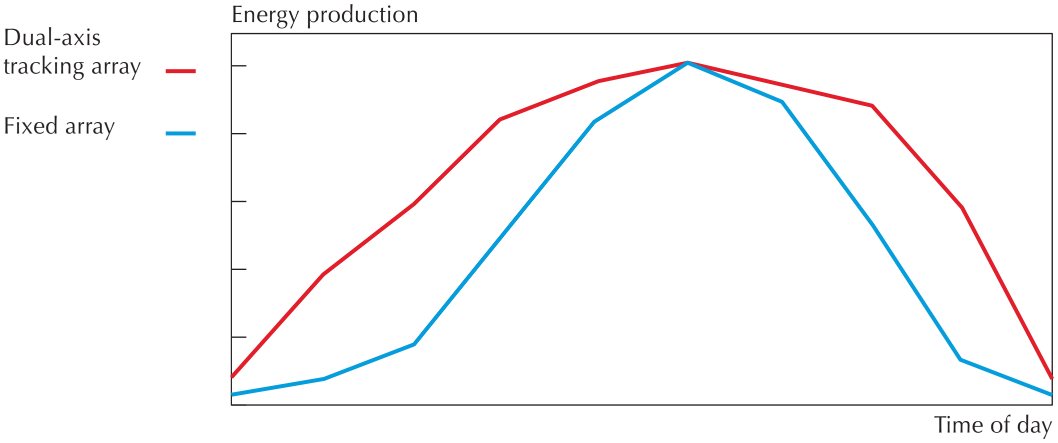
Solar PV and thermal can be merged into PVT collectors.

Concentrating photovoltaics

Using mirrors or lenses or a combination of both, concentrating PV (CPV) focuses the solar radiation on small, high-efficiency cells usually made of several layers (often called "tandem" or "sandwich") each capturing a specific wavelength of the solar light spectrum. One assumption is that the higher cost of these cells is outweighed by their higher efficiency (up to 38% for cells, 25% for modules) and the lower cost of the reflective surfaces or the lenses. CPV and PV, however, are not directly comparable; the primary criterion for choosing CPV is a high ratio of direct normal irradiance (DNI) to diffuse irradiance (as shown in Chapter 2). Another significant difference is the distinct daily profile of electrical output exhibited by sun-tracking systems (Figure 6.4). Tracking the sun is indispensable for CPV (with high accuracy for high concentrations, *i.e.* more than 10 "suns"), but optional (with low accuracy) for other PV technologies.

CPV requires effective cooling, which makes it easier to cogenerate heat and power (Photo 6.2). The heat can be used for some industrial process or desalination (see Chapter 5) or additional electricity generation. Concentrating photovoltaics and thermal (CPVT) designs are being explored in various forms.

Figure 6.4 **Output of tracking and fixed PV systems**



Key point

Two-axis tracking increases and evens out the production of PV over the day.

Organic cells

Emerging new technologies include advanced thin films and organic solar cells. Organic solar cells are either full organic cells (OPV) or hybrid dye-sensitised solar cells (DSSC). They have lower efficiencies and shorter life-times, but can be made using roll-to-roll and usual printing technologies, which could lead to very low manufacturing costs. They have a place in niche markets such as consumer devices, but it is yet unproven whether they will contribute to larger electric systems.

Novel devices: quantum dots and wells, thermo-electric cells

Research is underway on novel devices that may offer the possibility of breaking efficiency records – quantum dots and wells, and thermo-electric cells.

Most current PV cells are limited in efficiency to a theoretical maximum of about 30% for crystalline silicon because the photovoltaic effect takes place in only one "band" of solar radiation, corresponding to only one energy level of photons. Photons with lower energy levels fall short. Photons with greater energy levels work, but part of their excess energy is wasted for electricity and only heats the cell. It is possible to improve on this efficiency by stacking materials with different band widths together in multi-junction ("tandem" or "sandwich") cells. The same "trick" is used in most efficient thin films, but adding low-efficient layers at best allows reaching the efficiency level of c-Si cells. However, their complex manufacturing process and high costs reserve them for CPV devices.

This restriction may be overcome by quantum dots or nano-particles, which are semi-conducting crystals of nanometre (a billionth of a metre) dimensions. The wavelength at which they will absorb or emit radiation can be adjusted at will, so a mixture of quantum dots of different sizes can harvest a large proportion of the incident light. They can be moulded into a variety of different forms and processed to create junctions on inexpensive substrates such as plastics, glass or metal sheets. Quantum dots and wells might also be adjusted so that each highly energetic photon stimulates more than one electron. In both cases, efficiencies of more than 40% are conceivable at manufacturing costs that could remain relatively low; however, such results efficiencies are not yet achieved, even in laboratory research. Such breakthroughs would greatly improve the learning curve, but require major research effort.

Photo 6.2 **Dishes with CPV and heat collection**

Source: Zenith Solar, Israel.

Key point

CPVT is an appealing option if the heat collected can be used.

So-called thermo-photovoltaic cells offer another possibility, that of transforming the near infra-red radiation emitted by the sun, or radiant heat, into electricity (see Chapter 8).

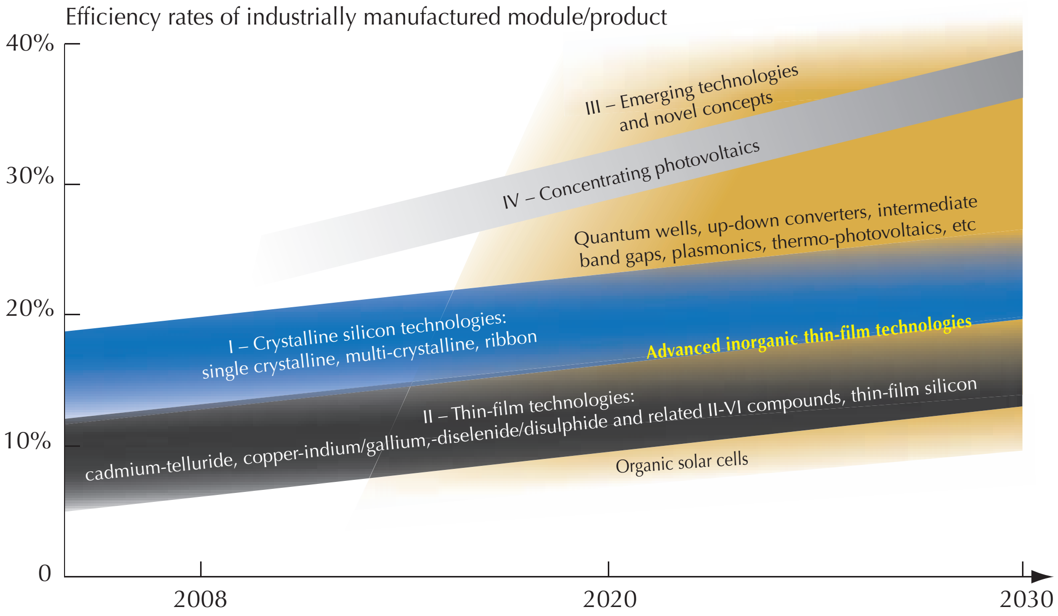
A synthetic view of the expected progression of efficiencies of successive generations of PV technologies is shown in Figure 6.5.

Balance of systems

Modules now represent more than half the cost of utility-scale PV systems, inverters and other balance of systems (BOS) costs account for one-third, and engineering and procurement the remainder. This share of BOS costs will likely grow. While the price of inverters decreased at the same pace as PV modules, prices for other BOS elements have not. The price of the raw materials used in these elements (typically copper, steel and stainless steel) has been more volatile. Installation costs have decreased at different rates depending on the type of application and maturity of the market. Reductions in prices for materials (such as mounting structures), cables, land use and installation account for much of the decrease in BOS costs.

Another contributor to the decrease of BOS and installation-related costs is the increase in efficiency at module level. More efficient modules imply lower costs for BOS equipment, installation and land use.

Figure 6.5 **PV technology status and prospects**



Source: IEA PVPS.

Key point

The future of PV is likely to be more diverse and more efficient.

Photovoltaic technologies can be applied in a very diverse range of applications, including small-scale residential systems, mid-scale commercial systems, large-scale utility systems and off-grid applications of varying sizes. They have different prices: the current and target system costs for the residential, commercial and utility sectors, updated from IEA, 2010*c* on the basis of recent information from the most mature market, Germany, are shown in Table 6.1, Table 6.2 and Table 6.3. In slightly more than one year, given actual cost reductions, deployment and trends, estimates for 2020 in particular have been significantly reduced. On top of the target costs (USD/kW) for typical turn-key system the tables indicate three different electricity generation costs (USD/MWh) depending on the electric output per kW capacity, which reflects different irradiance levels.

Current system prices may be significantly higher in less mature markets; however, it is reasonable to base target costs for the future on German data, as other markets will mature as they develop and prices would accordingly decline. These estimates are scenario-dependent, based on learning curves and deployment along the *ETP 2010* Hi-Ren Scenario. One may also question the assessment of future cost reductions on the basis of past learning progress. In many industries it has been observed that learning rates of mature technologies ultimately flattened as a result of a fully optimised product reaching an ultimate floor cost.

This has not yet been observed in the PV industry, and according to IEA analysis below, is unlikely to occur before 2050 for residential systems and before 2030 for commercial and utility-scale systems. Target costs for 2050 for those systems and the electricity they deliver (in italics in the relevant tables) are therefore more uncertain.

Table 6.1 **Cost targets for the residential sector**

		2010	**2020**	**2030**	**2050**
Typical turnkey system price (2010 USD/kW)		3800	1960	1405	1040
Typical electricity generation costs (2010 USD/MWH)*	2000 kWh/kW	228	116	79	56
	1500 kWh/kW	304	155	106	75
	1000 kWh/kW	456	232	159	112

Table 6.2 **Cost targets for the commercial sector**

		2010	**2020**	**2030**	**2050**
Typical turnkey system price (2010 USD/kW)		3400	1850	1325	*980*
Typical electricity generation costs (2010 USD/MWH)*	2000 kWh/kW	204	107	75	*54*
	1500 kWh/kW	272	143	100	*72*
	1000 kWh/kW	408	214	150	*108*

Table 6.3 **Cost targets for the utility sector**

		2010	**2020**	**2030**	**2050**
Typical turnkey system price (2010 USD/kW)		3120	1390	1100	*850*
Typical electricity generation costs (2010 USD/MWH)*	2000 kWh/kW	187	81	62	*48*
	1500 kWh/kW	249	108	83	*64*
	1000 kWh/kW	374	162	125	*96*

Notes: Based on the following assumptions: interest rate 10%, technical lifetime 25 years (2008), 30 years (2020), 35 years (2030) and 40 years (2050). Numbers in italics are considered more speculative.

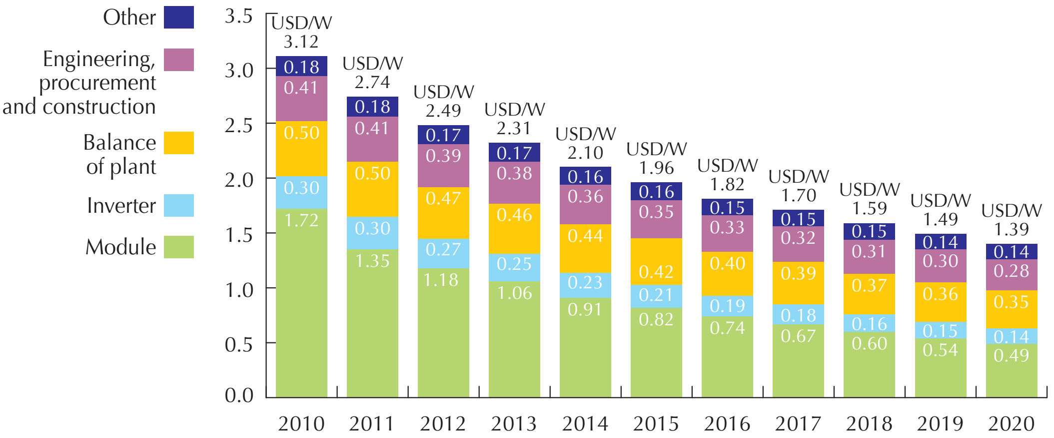
Sources: IEA 2010c, Bloomberg New Energy Finance, and IEA data and analysis.

Assumptions relative to the next ten years are more robust and based on detailed assessment of the various cost factors of PV systems. The price of silicon PV modules is expected to come down to one-third of its current level, and also one-third of future total system prices, against more than half at present (Figure 6.6).

Floor price and roof costs

Silicon is the second most widespread element on earth, available in sand and quartz rocks. The energy pay-back time of silicon PV cells (*i.e.* the time its electricity production takes to "repay" the energy associated with its fabrication) is currently between 1 and 1.5 years in southern Europe, despite the high energy cost of semiconductor-grade silicon (1 GJ/kg). Automated recycling is already an industrial reality: 95% of the modules, but only about 72% of the silicon, can be recycled. Some manufacturers already provide Si-PV systems with no silver contacts, thereby avoiding possible cost issues should a rapidly-expanding PV industry become a price maker for silver.

Figure 6.6 **Utility-scale PV price forecast**



Note: Module price derives from experience curve + margin; system price in markets with cost-based, rather than value-based pricing (such as Germany).

Source: Bloomberg New Energy Finance.

Key point

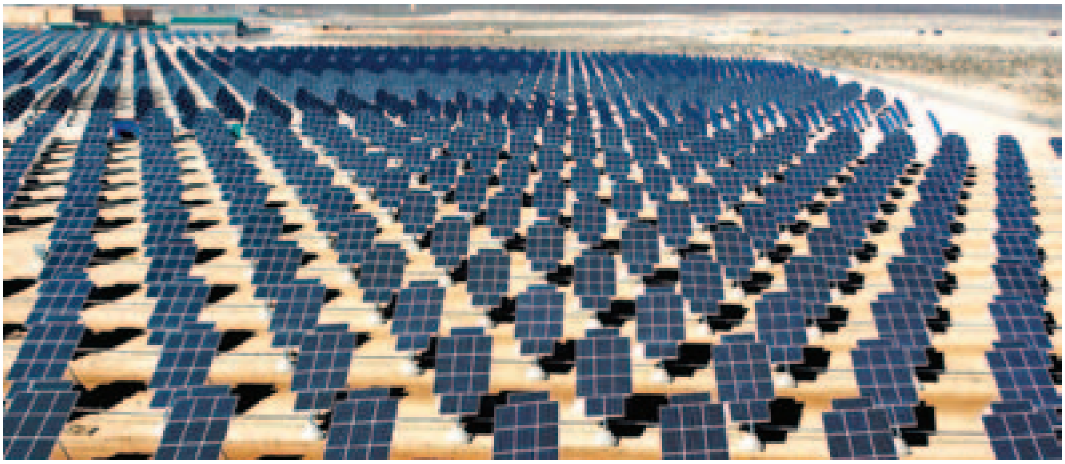
Module costs will soon represent only one-third of utility-scale PV systems.

If silicon is unlimited, some elements of non-silicon thin films are not. CdTe thin films need cadmium, a by-product of zinc mining, and tellurium, a by-product of copper processing. The latter's availability in the long term may depend on whether the copper industry can optimise extraction, refining and recycling yields. CIS and CIGS thin films need selenium, gallium and indium. The latter is found in tin and tungsten ores, but its extraction could drive the prices higher.

Overall, the target costs up to 2030 noted above appear in line with both historical experience and detailed consideration of future improvements. Beyond 2030, the learning curve may either slowly flatten out and reach what has been termed a PV "floor price", or experience new downward shifts as novel devices kick in. In both cases the USD 1/W_p mark for full PV systems will likely be hit and overcome, while some experts see the USD 0.50/W_p mark being ultimately achievable.

Building-integrated PV offers the possibility that a thin layer of PV-active material will become almost a standard feature of building elements such as roof tiles, façade materials, glasses and windows, just as double-glazed windows have become standard in most countries. With very large-scale mass production, and support elements having a primary role in building support or closure, the cost of PV would almost vanish in the market segment where it currently costs the most. PV roof costs may never meet a floor price.

Photo 6.3 **PV plants on Nellis Air Force Base, Nevada**



Source: U.S. Air Force photo/Airman 1st Class Nadine Y. Barclay

Key point

Utility-scale PV plants are emerging as a viable option.

Chapter 7
Solar heat

Capturing the sun's energy as heat is relatively easy, and can be done with considerable variety of devices, stationary or concentrating. The choice typically depends on the temperature levels required for end uses: water heating, space heating, space cooling, process heat, electricity generation or manufacturing of fuels. Storing heat is significantly less costly than storing electricity, but entirely offsetting seasonal variations of the solar heat at affordable costs remains a challenge.

Background

The use of solar heat is sometimes tracked back to Archimedes, who is said to have set fire to attacking Roman vessels with a giant mirror concentrating sunrays in 214 BCE, but there is no contemporary account of the siege of Syracuse to confirm the story. René Descartes thought the feat was impossible – but in April 1747 Georges Buffon set fire to a fir plank, besmeared with pitch, with 128 glasses concentrating sunrays.

In 1767, the Swiss scientist Horace de Saussure built the world's first solar collector, or hotbox. Astronomer John Hershel was inspired in the 1830s to hold little family cookouts with just such a box. William Adams, a British colonist, developed solar cooking in India to combat fuel wood depletion. Félix Trombe built a concentrating solar oven at Mont-Louis (French Pyrenees) in 1952, then a more powerful one at Odeillo in 1968.

On an industrial scale, at the end of the 19th century solar water heaters were developed in California, but the discovery of natural gas in the 1920s killed their expansion. In the 1960s, solar water heaters were installed by the million on Japanese and Israeli roofs. The boom expanded to other countries after the 1974 oil shocks but the 1986 counter-shock (oil glut) killed the nascent industry apart from in a few countries such as Israel, Germany and Austria. More recently, China dominated the global market for heating with domestic installations, mostly "thermo-siphon" solar water heaters based on evacuated tube collectors.

In 2010 solar heat collectors covered a global surface area of 28 000 hectares (ha), of which 16 500 ha was in China alone.

Solar heat today, despite the recent boom of PV, represents the largest solar contribution to our energy needs, with more than 196 gigawatt thermal (GW_{th}) of capacity and 162 terawatthour thermal (TWh_{th}) produced in 2010 (see Figure 4.1). It is second only to wind among the "new" renewable energy technologies (*i.e.* apart from hydro power and bio-energy). This comparison takes no account of passive solar energy in buildings.

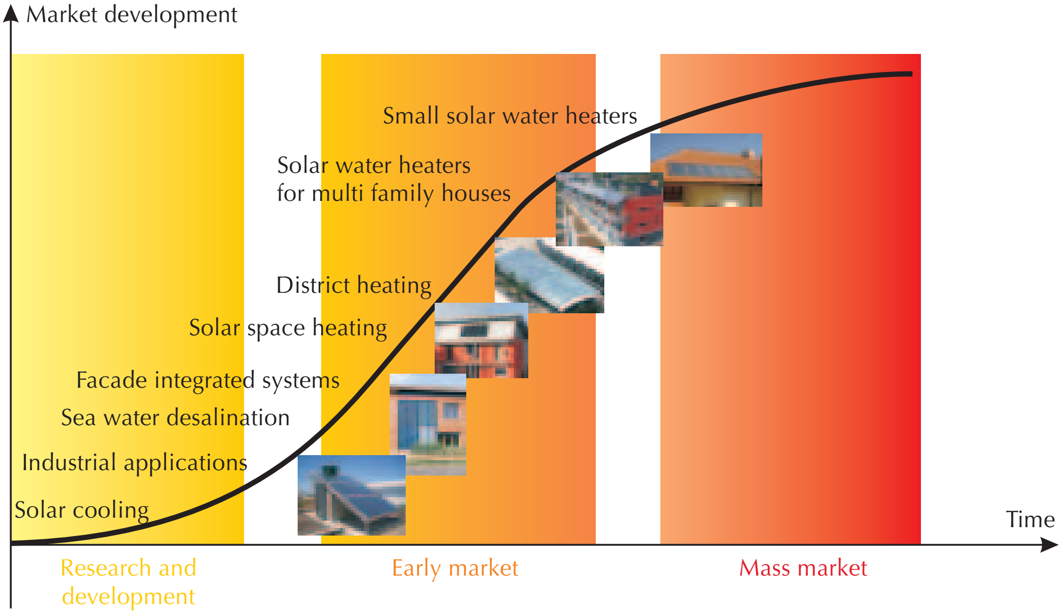
Collecting heat

Devices to capture solar energy as heat essentially offer a receptive surface to the sunlight, whether direct or diffuse. Absorption of solar rays heats those surfaces. To absorb as much incoming radiation as possible, black is the preferred colour.

The most simple devices, so-called "unglazed collectors", used for example to warm the water of swimming pools (mostly in Australia, Canada and the United States) or outside showers, are just black hoses lying on the ground or attached to the shower structure. Unglazed systems can also warm the air (see below under flat-plate collectors).

For higher temperature applications, including ensuring the availability of sanitary hot water, one must use flat-plate collectors or evacuated tubes. Advanced flat-plate and compound parabolic collectors (CPC) allow working temperatures of 100°C to 160°C. Concentrating collectors (Fresnel, parabolic troughs, dishes and towers or central receivers, ovens) allow much higher working temperatures – up to 2 500°C. Figure 7.1 illustrates various uses of solar heat and their respective levels of technology maturity.

Figure 7.1 **Various uses of solar heat at different technology maturity**



Source: Weiss, 2011.

Key point

Solar water heating for domestic use is the most wide-spread application.

Flat-plate collectors

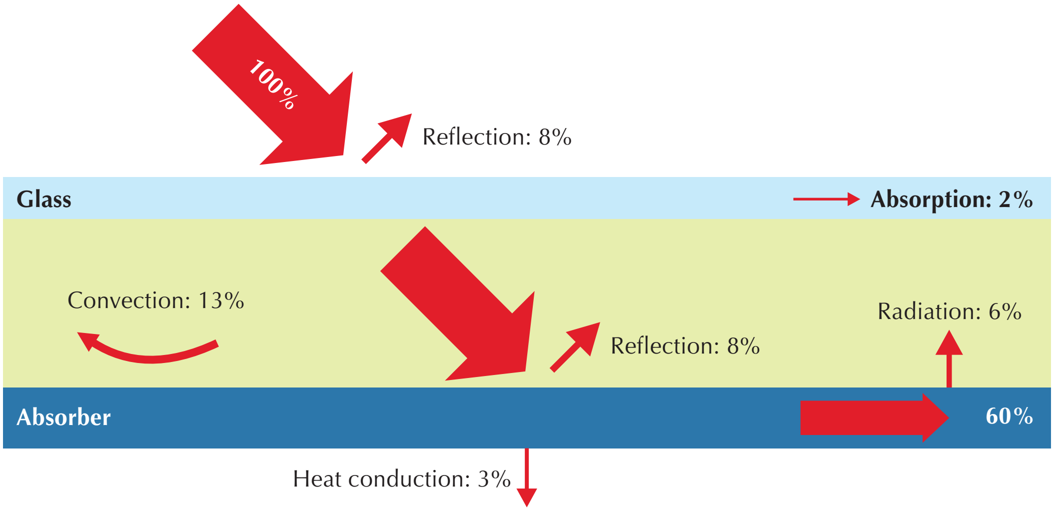
Flat-plate collectors are appropriate for lower demand hot water systems. They are also often more appropriate when snow accumulation is a problem, because the heat loss through a flat plate collector will often melt the snow.

Assembling a black surface in an isolated box with a glass cover makes a flat-plate collector. To retain as much heat as possible, it must be prevented from escaping through the back, sides or front. The radiation emitted by the heated surface is long-wave radiation, while the incoming radiation is much shorter-wave. Glass has the property of being relatively opaque to long-wave radiation – radiant heat – while letting the incoming light through.

Solar radiation enters the collector through the transparent cover and reaches the absorber, where the absorbed radiation is converted to thermal energy. A good thermal conductivity is needed to transfer the collected heat from the absorber sheet to the absorber pipes, where the heat is transferred to a fluid. Usually a water/glycol mixture with anticorrosion additives is used as the heat-carrying fluid. The fluid also protects the collector from frost damage.

Standard flat-plate collectors can provide heat at temperatures up to 80°C. Loss values for standard flat-plate collectors can be classified as optical losses, which grow with increasing angles of the incident sunlight, and thermal losses, which increase rapidly with the working temperature levels (Figure 7.2). As can be seen, the efficiency of flat-plate collectors is as high as 60%. In the same range of temperatures, advanced flat-plates or evacuated tubes have even higher efficiencies, which compare very favourably with those of photovoltaic (PV) or concentrating solar power (CSP).

Figure 7.2 **Optimal and thermal losses of a flat-plate collector**



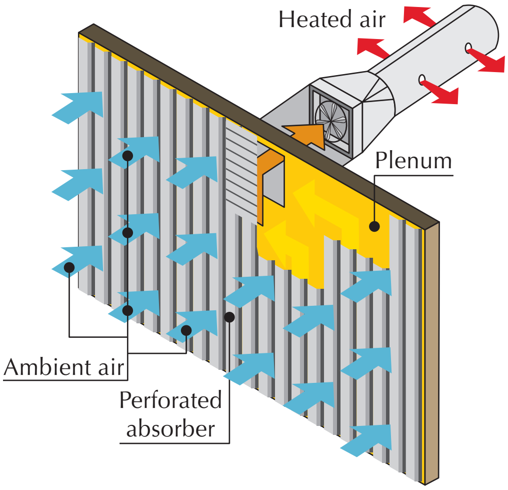
Source: IEA-SHC, 2008.

Key point

Good design and manufacturing minimise heat losses in flat-plate collectors.

The vast majority of flat-plate collectors use water as the heat-transfer fluid (HTF), often complemented with glycol to prevent freezing; a minority use air. Air collectors cannot freeze or boil and have no corrosion issues, and they are lighter than liquid-based. They can be unglazed perforated plates or "transpired air-collectors" (Figure 7.3), or glazed flat-plate collectors. Air collectors are usually used for ventilation heating, and in agro-industries for crop and food drying. When used in buildings, they are hard to distinguish from passive solar designs (see Chapter 4).

Figure 7.3 **Transpired air collectors**



Source: NREL.

Key point

Unglazed solar air collectors provide heated air to buildings or agro-industries.

To improve on standard flat-plate collectors, some of the main losses need to be reduced. Anti-reflective coating can reduce reflections to 4% to 7%. Coating the absorber can reduce the radiation losses. To reduce the main losses from convection through the front, hermetically sealed collectors with inert gas fillings, double covered flat-plate collectors, or vacuum flat-plate collectors may be used.

Evacuated tube collectors

Evacuated tube collectors can produce higher temperatures in the HTF and therefore are often more appropriate for constant high-demand water heating systems or process loads. Evacuated tubes can show a good efficiency even for temperatures as high as 170°C. All evacuated tube collectors have similar technical attributes:

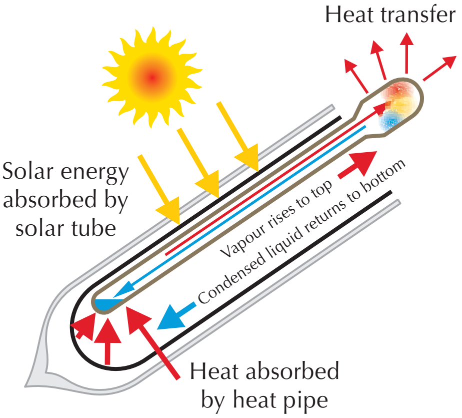
- A collector consisting of a row of parallel glass tubes;
- A vacuum ($< 10^{-2}$ Pa) inside each tube that drastically reduces conduction losses and eliminates convection losses;
- The form of the glass is always a tube to withstand the stress of the vacuum;
- The upper end of the tubes is connected to a header pipe; and
- A getter using absorbent material maintains the vacuum and provides visual indication of the vacuum status.

Evacuated tubes contain a flat or curved absorber coated with a selective surface and fluid inlet/outlet pipes. Inlet and outlet tubes can be parallel or concentric. Alternatively, two concentric glass tubes are used, with the vacuum between them. The outside of the inner tube is usually coated with a sputtered cylindrical selective absorber.

Evacuated tube collectors can be classified in two main groups:

- **Direct flow tubes:** the fluid of the solar loop circulates through the piping of the absorber;
- **Heat pipe tubes:** the absorbed heat is transferred by using the heat pipe principle without direct contact with the HTF of the solar loop (Figure 7.4). One advantage of such a scheme is that collectors continue to work even if one or several tubes are broken. Damaged tubes can be easily replaced.

Figure 7.4 **Heat pipe tube**



Source: Apricus Solar Co. Ltd.

Key point

Evacuated tubes are now the most popular solar collectors in China

CPC collectors

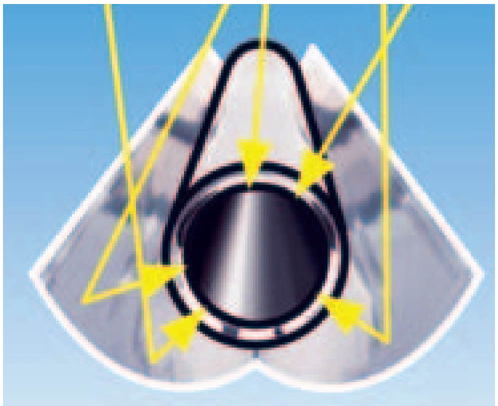
Compound parabolic collectors concentrate the solar radiation on an absorber (Figure 7.5). Because they are not focusing (non-imaging), they accept most of the diffuse radiation and are not restricted (like plain concentrating technologies) to direct "beam" radiation (see Chapter 2). CPC collectors do not need to track the sun and are stationary or require only seasonal tilt adjustments. This publication includes stand-alone CPC collectors are included with non-concentrating devices. If they concentrate the sun's rays by only a small factor (less than 10 "suns", often only 2 or even less) this is enough to allow non-evacuated collectors to achieve working temperatures up to 100°C with an efficiency comparable to that of evacuated tubes.

Some evacuated tube collectors routinely include small CPC collectors inside the tubes. Future designs with fewer tubes per surface area and CPC are expected to deliver efficiencies of 60% at working temperatures of 160°C or 50% at temperatures of 200°C with fully stationary collectors.

Ovens

Solar ovens collect the energy from the sun with or without concentration. Box cookers look like a flat-plate collector with a larger internal space, inside which one can place what needs to be heated or cooked (Photo 7.1). With one or several reflectors, a box cooker is similar to a CPC collector, with low concentration level.

Figure 7.5 **CPC collector concentrating diffuse light**



Source: Ritter Solar.

Key point

At low concentration levels CPC collectors need not track the sun.

Photo 7.1 **Solar box cookers**

Source: Atlas cuisine solaire.

Key point

Solar box cookers for cereals and vegetables help to reduce use of fuel wood.

The lowest-cost options consist of only such reflectors, and possibly clear glass salad bowls up-turned over the pot or plastic bags (Photo 7.2). Such "panel cookers" or "funnel cookers" are produced from recycled materials in some developing countries for as little as USD 2.00.

Photo 7.2 **Cheapest solar cookers in Sudan**

Source: Sudan Envoy, Solar Cookers pt. II.

Source: Cédric Filhol.

Key point

Solar cookers can be made from recycled materials at a very low cost.

Both devices allow for cooking many types of food. To toast, roast, grill or brown food, however, higher temperature levels are needed, requiring concentration. This is achieved with a reflecting parabola (Photo 7.3). Sun-tracking is manually handled by the cooks. For larger volume cooking at community level, other systems are used, in particular Scheffler dishes described below.

Photo 7.3 **Concentrating solar cooker**

Source: Crosby Menzies/SunFire Solutions

Key point

Concentrating solar ovens can toast any food.

Concentrating ovens are not limited to cooking food. Mid-size devices can achieve a wide range of temperature levels and power ranges (50 kW_{th} for the solar oven in Photo 7.4), so that they can be used for artworks and industry, such as for potteries in Morocco as mentioned (see Chapter 5).

Photo 7.4 **Mid-size industrial solar oven at Mont-Louis (French Pyrenees)**

Source: Four Solaire Développement.

Key point

Mid-size solar ovens can achieve temperatures of several hundreds °C and be used by small industries.

Such ovens have two stages of reflection: the first, using one or many heliostats[1], tracks the sun; the second, using a very large parabola, concentrates its rays on a fixed target. Industrial solar ovens have very high concentration levels, which can reach high temperatures with significant power. (Figure 7.6)

The world's largest solar ovens are in Odeillo (French Pyrenees) and in Parkent (Uzbekistan). Due to excellent solar irradiance, the one in Odeillo is more powerful with 1 MW_{th} (Photo 7.5). With a concentration ratio of 10 000 "suns", it brings the target to temperatures up to 3 500°C – with no combustion residues. Industrial solar ovens are mostly used for scientific and technical experiments, such as testing the resistance of new materials.

Why concentrate the sunlight

Discussion of solar ovens brought us progressively into the area of concentration. Before going farther, it is useful to consider how concentrating solar rays allows collecting solar energy at higher working temperatures. This higher temperature offers a better efficiency in the conversion of heat to electricity, in case of a power plant (see Chapter 8), or may be needed to run industrial processes (Chapter 5) or chemical reactions in manufacturing solar fuels (Chapter 9).

However, reaching high temperatures per se is not enough – it must be done with good efficiency at the collector level. If the heat is not removed, the temperature will increase to the point where the thermal losses equal the solar inputs, called the stagnation temperature, and no useful energy is made available. Indeed, the efficiency in collecting heat decreases

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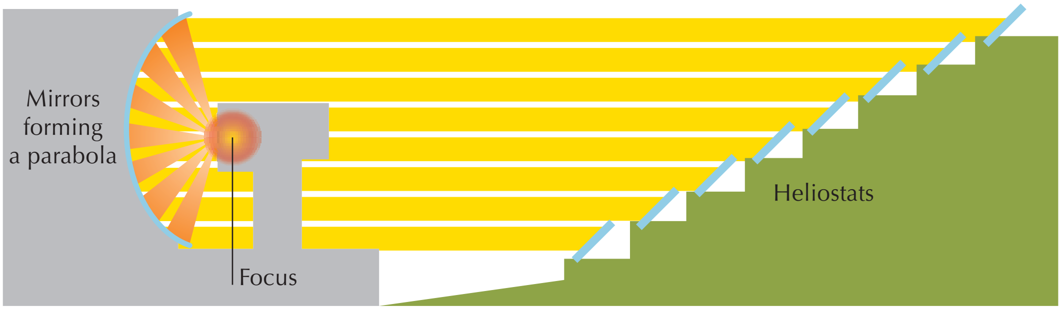
[1] A heliostat is a device with a mirror that turns so as to keep reflecting sunlight toward a predetermined target, compensating for the sun's apparent motion in the sky.

with the temperature, so the working temperature of the best stationary, flat-plate or evacuated tubes collectors, even CPC collectors with only one-digit concentration ratio (<10), is kept lower, and most often significantly lower, than 200°C.

Figure 7.6 **Working scheme of a solar oven**



Source: Wikipedia.

Key point

Sun-tracking and concentration are distinct steps in solar ovens.

Photo 7.5 **The solar oven at Odeillo (France)**

Source: Wikipedia.

Key point

Large solar ovens produce ash-free high-temperature heat for various purposes.

Significant concentration is the key to reaching higher temperature levels. However, as explained above (Chapter 2), concentrating sunrays uses only direct irradiance, and requires precise tracking systems, depending on the concentration ratio. Hence the distinction between the linear devices that follow the sun on one axis, such as hemi-cylindrical parabolic troughs and linear Fresnel reflectors, and the point focus devices that follow the sun on two axis, such as parabolic dishes and solar towers. Linear devices usually reach two-digit concentration ratios (<100), or dozens of suns, while the point focus devices reach three-digit concentration ratios, or hundreds of suns – even more as in the case of industry/research ovens.

Parabolic troughs

Parabolic trough systems consist of parallel rows of mirrors (reflectors) curved in one dimension (*i.e.* semi-cylindrical) to focus the sun's rays. The mirror arrays can be more than 100 m long with the curved surface 5 m to 6 m across. The heat collectors are stainless steel pipes (absorber tubes) with a selective coating (designed to allow pipes to absorb high levels of solar radiation while emitting very little infra-red radiation). The pipes are insulated in an evacuated glass envelope.

Simple small installations can have the trough rotate around a fixed pipe. With increased sizes however, the mechanical forces soon become intractable and the rotation axis must be set at the gravity centre of the device. This creates the need to move absorber tubes and therefore ball joints or flexible hoses subject to potential leakages. The use of a low-pressure HTF (synthetic oil) is the standard with troughs; direct steam generation is currently under study.

Parabolic troughs are the most widely used concentrators for solar thermal electricity (STE) today (see Chapter 8) and represent 90% of the current market. Electricity generation currently represents an even greater share of the market for parabolic troughs. Other applications, such as rooftop devices to cogenerate heat, electricity and cold, and industrial process heat applications, are commercialised, notably in the United States.

Parabolic troughs are usually oriented along a north-south axis and track the sun from east to west. Orientation along an east-west axis would collect less energy over the year, but more during the winter by reducing the cosine losses[2] resulting from the sun being low in the sky. Combining both orientations in a single facility has been suggested but never put into practice.

A new step could possibly be reached with mirror-film reflectors of much larger size than current glass-made troughs (Photo 7.6). Increased concentration factors would allow increasing working temperatures while keeping good collector efficiencies, but would require new HTF or working fluids.

At the linear focus of the semi-cylindrical parabola, the heat collector element is designed to capture as much of the solar flux as possible, while minimising radiation and convection thermal losses. The capture is facilitated by selective coating of the receiver tube, and minimising losses by an evacuated transparent glass envelope. Different heat transfer or working fluids can be piped through the collectors, depending on the use of the installation.

Parabolic troughs have a relatively good optical efficiency but need to be distanced from each other to minimise shading, which happens when a mirror on the trough intercepts part of the solar flux incident on another.

Fresnel reflectors

Linear Fresnel reflectors (LFRs) approximate the parabolic shape of trough systems, but use long rows of flat or slightly curved mirrors to reflect the sun's rays onto a downward-facing linear, fixed receiver. Compact linear Fresnel reflectors (CLFRs) use two parallel receivers for each row of mirrors (Figure 7.7).

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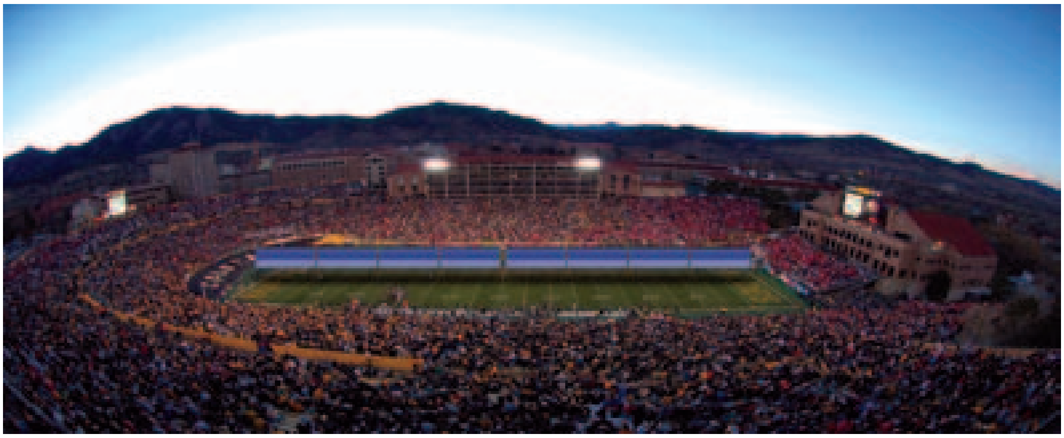
[2] *Cosine loss is energy lost by not facing the sun's rays directly.*

Photo 7.6 **Possible future mirror-film troughs, pictured in a stadium for illustration**

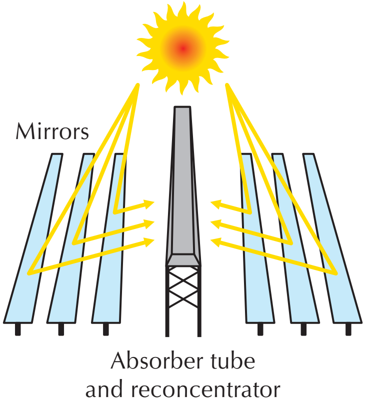


Source: SkyTrough®.

Key point

Parabolic troughs are mature linear concentrating devices.

Figure 7.7 **Compact linear Fresnel reflectors**



Key point

Linear Fresnel reflectors are less costly than troughs but less effective when the sun is low.

Linear Fresnel reflectors have a lower optical efficiency than troughs, due to greater cosine losses, if one compares the efficiency in the capture of the energy that falls within the apparatus. This makes them less effective than troughs at times of low sun, in the early morning and late afternoon. However, they offer a smaller footprint than other technologies, as the high position of the receiver allows the troughs to be installed close to each other. They are less costly to build than parabolic troughs, and can use CPC collectors around the receiver to somewhat increase concentration levels. They usually have very effective back side insulation. The fixed receiver allows for high pressure and thus direct steam generation.

Parabolic dishes

Parabolic dishes concentrate the sun's rays at a focal point above the centre of the dish. The entire apparatus tracks the sun, with the dish and receiver moving in tandem. Parabolic dishes offer the best optical efficiency, as they entail no cosine losses.

Different systems can be used to track the sun on two axes. One is the equatorial mount, with which an axis is set parallel to that of the earth: a continuous rotation at a constant rate during the day compensates for the earth's rotation, while discrete adjustments follow the changes in the sun's elevation over the seasons. In small devices, the adjustment can be made manually, so operation can be quite simple.

A more common double-axis system is the alt-azimuth mount, which is based on a horizontal rotation and direct command of the elevation, with the two axes perpendicular to each other. Alt-azimuth mounts are usually preferred in large installations with many dishes, for their precision, mechanical simplicity and robustness. They do, however, require variable speed motions on both axes to track the sun.

A few large experimental parabolic dishes have been built in Australia. But usually individual dishes are relatively small and assembled in large numbers, so the heat received at each focus point can be collected and gathered. Although this scheme has been used in one industrial installation in the United States, it has now been abandoned, as the limitations in piping material, transport fluids, and joint technology seem to preclude transfer of heat at the high temperatures that such concentration levels provide. Today, almost all parabolic dishes are designed as independent electricity generators.

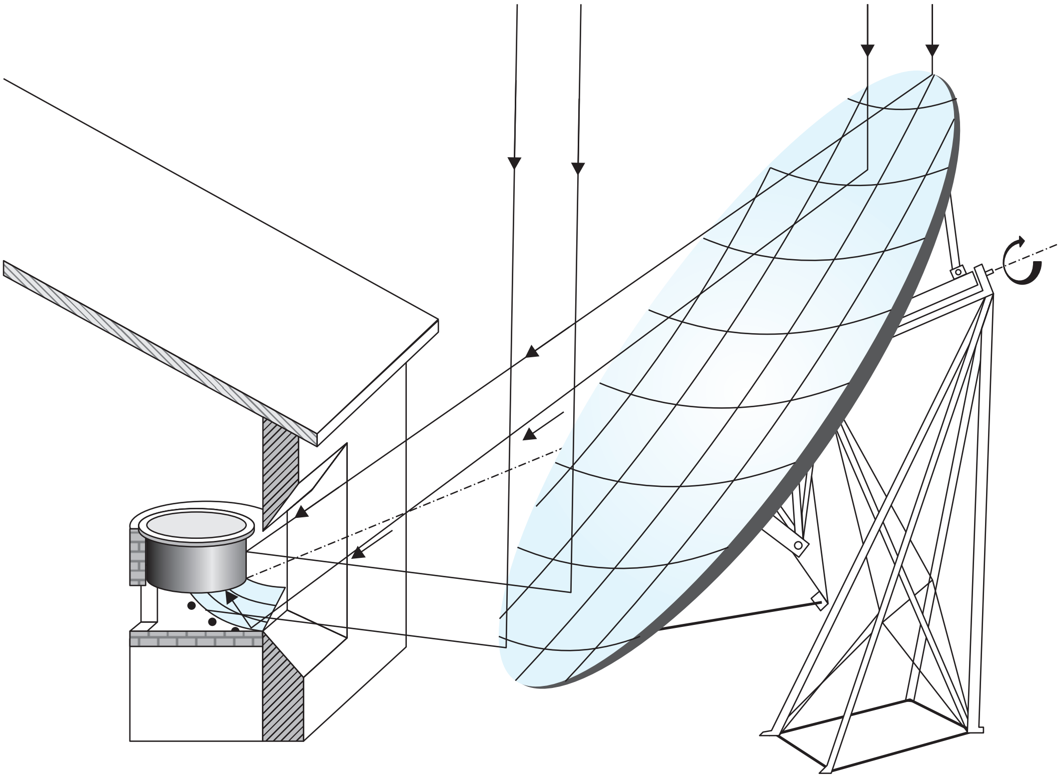
Scheffler dishes

Scheffler dishes are made of a light flexible steel frame with many small pieces of mirror. They are formed into a flexible parabola focusing the sun's rays on a fixed receiver. They rotate on an axis parallel to that of the earth, making an angle with the horizontal equal to the latitude. This allows tracking the sun during one day with a single rotational mechanism. A simple clock mechanism can be used, and the drive requires minimal power. Adjustment of the direction of the parabola, to follow the sun's height across the seasons, is made manually every few days. A continuous deformation of the surface of the parabola over the year allows the sun's rays to be effectively concentrated on the fixed target. The surface deformation takes place automatically as the direction of the parabola is adjusted at sunset to direct the concentrated reflective beams on the receiver (Figure 7.8).

Output obviously depends on the solar resource. Under Indian skies, where most Scheffler dishes have been locally built and installed at a cost of USD 1 450 to USD 2 900 (EUR 1 000 to EUR 2 000), a ten-square metre dish provides about 22 kWh per day.

A further development combines two Scheffler dishes, one "standing" and the other "sleeping" to target one receiver. This allows keeping the total effective aperture constant throughout the year. This approach is most often used to produce steam collected by pipes (as on Photo 7.7) and it could also be used for solar ovens with secondary reflectors.

Figure 7.8 **Scheffler dish for community kitchen**



Source: Wolfgang Scheffler, www.Solare-bruecke.org.

Key point

Using a simple clock mechanism, Scheffler dishes concentrate sunrays on a fixed focus.

Solar towers

Solar towers, or central receiver systems, are made of a field of heliostats surrounding a central receiver atop a built structure (Figure 7.9). Heliostats reflect the sunlight onto the receivers. Alt-azimuth mounting of heliostats is almost universal in towers. The simplicity of equatorial mount for dishes is lost with heliostats, because their surface area is not perpendicular to the pointing direction, but to the bisect of the angle formed by the direction of the sun and that of the tower.

Heliostats can vary greatly in size, from about 1 m^2 to 160 m^2. The small ones can be flat and offer little surface to winds. The larger ones need to be curved to send a focused image of the sun to the central receiver, and need strong support structures and motors to resist winds. For similar collected energy ranges, however, small heliostats need to be grouped by the thousand, multiplying the number of motors and connections, and their orientation requires much more computing power. As the cost of computing power is rapidly declining, the trend towards more and smaller heliostats is likely to persist. Heliostats need to be distanced from each other to reduce shading but also blocking, which takes place when a heliostat intercepts part of the flux reflected by another (Figure 7.10).

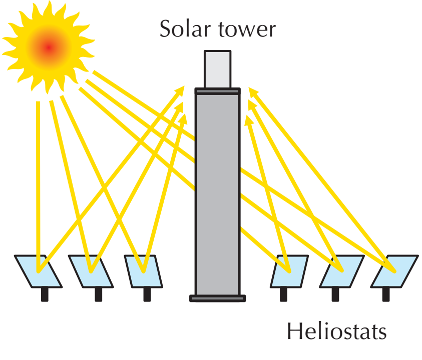
Photo 7.7 **Scheffler dishes associated in pairs in a cooking system at Hyderabad (India)**

Source: Deepak Gadhia.

Key point

Pairing Scheffler dishes helps obtain even sunlight throughout the year.

Figure 7.9 **Towers (central receiver systems)**

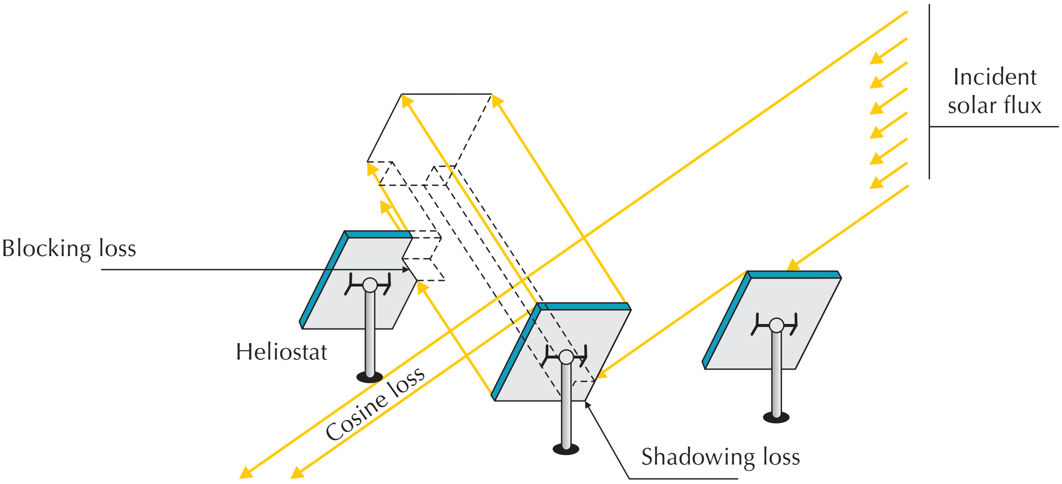


Key point

Towers offer higher large-scale concentration levels.

Field size seems to be limited to a thermal power of about 600 MW_{th}, for which heliostats are located about 1.5 km from a tower of about 160 m height. Longer distances would further complicate the exact directing of the reflected sun on the tower, while atmospheric attenuation near ground level would reduce the energy flux.

Figure 7.10 **Blocking, shading and cosine losses in heliostat fields**



Source: Stine and Geyer, 2011.

Key point

Heliostats must be distanced from each other to minimise blocking and shading.

Field design optimisation also depends on the desired power. Typical heliostat fields in low latitudes tend to be circular and surround the central receiver, while in higher latitudes they tend to be semi-circular, to reduce cosine losses. Small fields will be more concentrated to the polar side of the tower, larger ones more circular, as atmospheric attenuation reduces the efficiency of far-field heliostats.

While linear systems require flat land areas, central receiver systems may accommodate some slope, or even benefit from it as it could reduce blocking and shadowing, and allow increasing heliostat density.

There are two basic receiver designs: external and cavity. External receivers offer vertical pipes to the concentrated solar flux from the heliostats, in which a heat transfer or working fluid circulates. In case of direct steam generation, different heliostats might be pointed to two or three different stages where the water is pre-heated, then vaporised, and if required the steam superheated. In the cavity design, the solar flux enters the cavity, possibly closed by a window.

"Beam-down" designs use a secondary reflector on top of the tower, of hyperboloid shape, which redirects the concentrated solar flux to ground level, where it might be refocused by a secondary compound parabolic concentrator before it falls on the receiver (Photo 7.8). This design, conceived and first assembled at the Weizmann Institute in Israel, reduces optical efficiency but conveniently allows keeping the receiver at ground level.

Heat transfer or working fluids, or reactants, are specific to the applications and are described in Chapters 5, 8 and 9.

Recently, scientists at the Massachusetts Institute of Technology have suggested a simpler concept called CSPond – provided hilly landscape. Light from a hillside of mirrors goes through a small open window in a small insulated building and is volumetrically absorbed into the liquid salt over a distance of several meters. The system absorbs light and stores energy in the liquid salt, from which it is extracted and turned into electricity at will – thanks to thermal storage (Forsberg, 2010).

Photo 7.8 **Experimental beam-down solar tower in Abu Dhabi**

Source: Yutaka Tamaura, Tokyo Institute of Technology.

Key point

Beam-down design avoids putting heavy and complex receivers on top of towers.

Storing the sun's heat

Thermal storage is a critical component in achieving high penetration levels with solar energy technologies. It needs to compensate for the variability of the solar resource and increase the capacity factors or value of the solar systems. It has applications in all solar applications: solar water heating, solar heating and cooling, solar process heat, solar thermal electricity, and even the manufacturing of solar fuels (which constitute a specific sort of transportable stored solar energy).

There are several ways to store the heat collected from the sun. One, "sensible heat," works by modifying the temperature of some medium. Another is "latent heat," in which the phase of some medium is changed – from solid to liquid, or from liquid to gaseous states – when the heat is being stored and in the opposite direction when the heat is extracted. The storage medium can be the final desired product, such as hot water for sanitary or other purposes, or a specific medium introduced in a solar system for storage purpose. Table 7.1 shows the relevant characteristics of various media for sensible heat.

Water has a high calorific value, as shown by its specific heat value in J/m^3/°K. But above 100°C, it needs to be pressurised which, depending on the pressure, may significantly complicate the storage system. Despite lower specific value and thanks to higher temperature ranges, molten salts currently are the preferred option in generation of electricity. Two-tank (hot and coled) storage systems are standard, as on Figure 8.2, while development on single-tank systems, as on Figure 9.2, are underway, with potential cost reductions. Stones and other inert materials with very low costs, or even negative costs in case of specific waste people pay to get rid of (*e.g.* vitrified asbestos wastes) can be used as well. Heat exchanges may be difficult with solid materials, since they occur only through conduction. Convection of liquid media is much more effective.

Table 7.1 **Characteristics of some possible storage media**

Material	Temp. range	Density	Specific heat	Specific heat	Total heat
	°C	kg/m^3	J/kg/ °K	J/m^3/°K	MJ/m^3
Water (1 atm)	0-100	1 000	4 190	4.19	419
Molten salts	142-540	1 680	1 560	2.62	1 043
Liquid sodium	100-760	750	1 260	0.96	520
Cast iron	< 1 100	7 200	540	3.89	2 138
Aluminium	< 650	2 700	920	2.48	1 366
Rock	...	2 600	890	2.31	1 271

Sources: Welle, 2010.

Key point

Sensible storage heat can use a variety of media.

Another option is that of latent heat, *i.e.* the heat that is absorbed by a solid that melts or a liquid that boils, and the heat freed by a gas that condenses or a liquid that solidifies. In practice, phase change materials (PCMs) used for thermal storage change only from solid to liquid states and vice versa. When heated, PCMs first rise in temperature, like sensible storage media. When the temperature reaches the melting point, PCMs absorb large amounts of heat at constant temperature, until entirely liquid. When it releases its stored latent heat, the PCMs solidify. Many PCMs are available in a large temperature range (from -5°C up to 190°C). They store 5 to 14 times more heat per unit volume than sensible storage materials.

Thermo-chemical storage is an indirect way to store heat. The heat is not stored directly as sensible or latent heat but by way of a physicochemical process, such as adsorption or absorption, that consumes heat in charging mode and releases heat in discharging mode. The sorption material can be a porous solid (*e.g.* silica gel, zeolite) or salt-hydrate solutions with a high affinity for water (the sorption material releases water vapour when heated and releases heat when water vapour is adsorbed or absorbed). Many compounds result in products that can be stored over long periods without significant energy loss, making long-term heat storage possible.

Thermo-chemical storage offers high energy density, reducing storage volumes. Many of these systems act as heat pumps, making cooling as well as heating possible. However, they are more complex, use expensive compounds, and require relatively high temperatures. Thermo-chemical storage systems can be divided into open and closed systems. Open systems, such as sorption processes for desiccant systems based on the adsorption, release water/steam into the environment. Closed systems isolate the working fluid from the atmosphere.

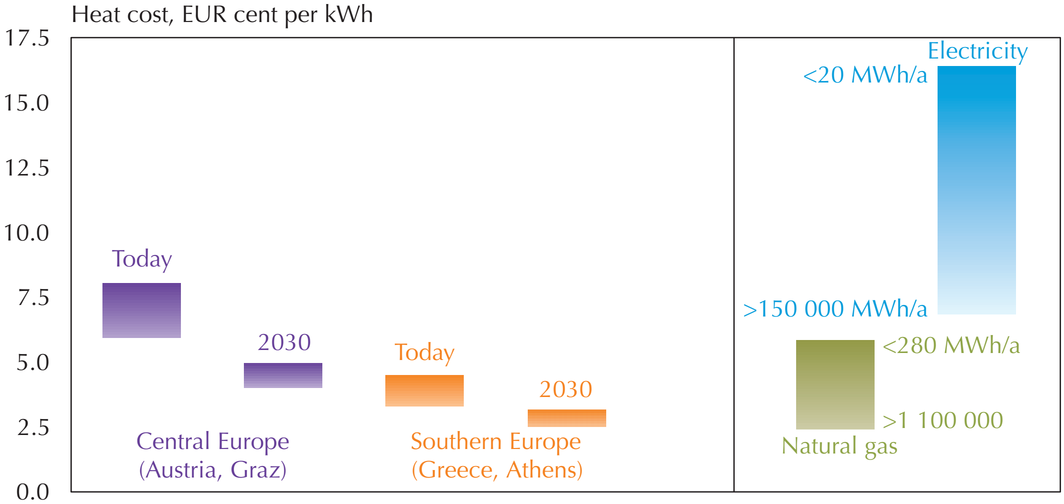
Thermal storage for daily or weekly applications is generally affordable. Storage for longer periods of time is more challenging. The possibilities appear to be either inexpensive sensible heat storage media or high energy density systems. To limit volume (other than using the soil), developers of space heating systems put their hopes in the development of efficient and affordable thermo-chemical storage systems (see Chapter 4). Because most CSP plants are located in semi-desert areas, and thanks to their high working temperatures, seasonal thermal storage could perhaps be achieved with inexpensive media, such as stones (see Chapter 8).

Thermal storage finally includes various means to store cold, not only heat. A simple but efficient example is making ice from thermally driven cooling devices. Melting of the ice will deliver cold when needed.

Costs of solar heat

The actual costs of solar heat are more difficult to define than for other applications of solar energy, as they depend not only on the resource – which is free – and the technology – which is not – but also from the effective use of the heat collected, which can be significantly variable. Figure 7.11 shows estimates of solar heat costs for solar supported heating networks and low-temperature industrial process applications, today and in 2030, under two different resource regimes in Europe. Chapter 4 gives information on costs for solar water heaters.

Figure 7.11 **Price of solar thermal generated heat *versus* conventional energy sources, for solar supported heating networks and low temperature industrial process applications > 350kW$_{th}$**



Source: Weiss, 2011.

Key point

Low temperature solar heat will become more broadly competitive for district heating services and industry.

Chapter 8
Solar thermal electricity

Solar thermal electricity is a proven technology with close to 30 years of experience. Its strengths rest in its ability to make electric capacities firm and to time-shift electricity generation, thanks to thermal storage. STE can also be part of a hybrid plant, lowering the cost of solar electricity. STE only exists today as concentrating power plants (CSP) in arid and semi-arid regions. The trend is to increased working temperatures, and to towers with a great variety of designs and applications. Non-concentrating solar thermal electricity may offer new options with storage under a greater variety of climates.

Background

In 1878, Augustin Mouchot and Abel Pifre built several concentrating solar systems, based on dishes, one producing ice in 1878, another the following year running a printing press in the Jardin du Palais Royal in Paris. They then built small solar desalination plants in Algeria. The American engineer John Ericsson built similar devices in the United States around 1884, based on parabolic troughs.

In 1907, Shuman exhibited in Philadelphia a non-concentrating solar motor consisting of about 100 m^2 of hotbox collectors filled with water and laced with iron pipes containing ether, which has a relatively low boiling point. Vapour resulting from the solar-heated ether powered a 560-watt steam engine used to pump a continuous stream of water. Six years later in Maadi, then a small farming village on the banks of the Nile several miles south of Cairo, the same Shuman built an irrigation plant run by solar energy, using parabolic trough-shaped mirrors to concentrate the sun's rays on water pipes, producing steam running a steam-engine (Photo 8.1). World War I and the growth of the oil industry ended these developments, despite the German Parliament voting credits in 1916 for building CSP plants in German "South-West Africa", now Namibia.

Electricity was not part of these early attempts, but mechanical power is easily transformed into electricity. At the time of the first oil shock, several countries developed research programmes on concentrating solar power, and the IEA launched one of its most successful "implementing agreements" – Small Solar Power Systems (SSPS), now called SolarPACES, building a solar tower and a parabolic trough plant in Almeria, Spain. France, Italy, Japan, Russia, Spain and the United States built experimental solar towers in the early 1980s. From 1984 to 1991 the Luz Company built nine commercial CSP plants in California, most of which are still up and running today, delivering solar electricity to the grid of the utility Southern California Edison.

Concentrating solar power

As explained in Chapter 7, concentrating the solar rays allows higher working temperatures with good efficiency at collector level. This, in turn, allows a better efficiency in the conversion of the heat into mechanical motion and, thus, electricity, as a consequence of the Carnot theorem. The ideal Carnot efficiency is defined by the ratio of the difference in temperatures of the hot and the cold source, divided by the absolute temperature (in Kelvin) of the hot source. Receiver efficiencies, Carnot efficiencies of the conversion into electricity, and total solar to electric efficiencies, are shown on Figure 8.1 in the function of the working temperature for various concentration ratios or "suns". On the left diagram, ratios of 40 to 100 suns are representative of linear concentration systems. On the right diagram, ratios of 100 to 2 000 suns are representative of point-focus systems. The efficiency of the receiver depends on the state of the technology, while the Carnot efficiency represents a physical law and expresses the maximum possible efficiency of the conversion. The global efficiency is the product of the efficiency of the collector by the Carnot efficiency and a fixed coefficient, set at 0.7, expressing the imperfection of the thermodynamic engine.

Photo 8.1 **Shuman's concentrating solar thermal plant in Maadi, Egypt, 1913**

Source: Ruiz Hernandez, 2010.

Key point

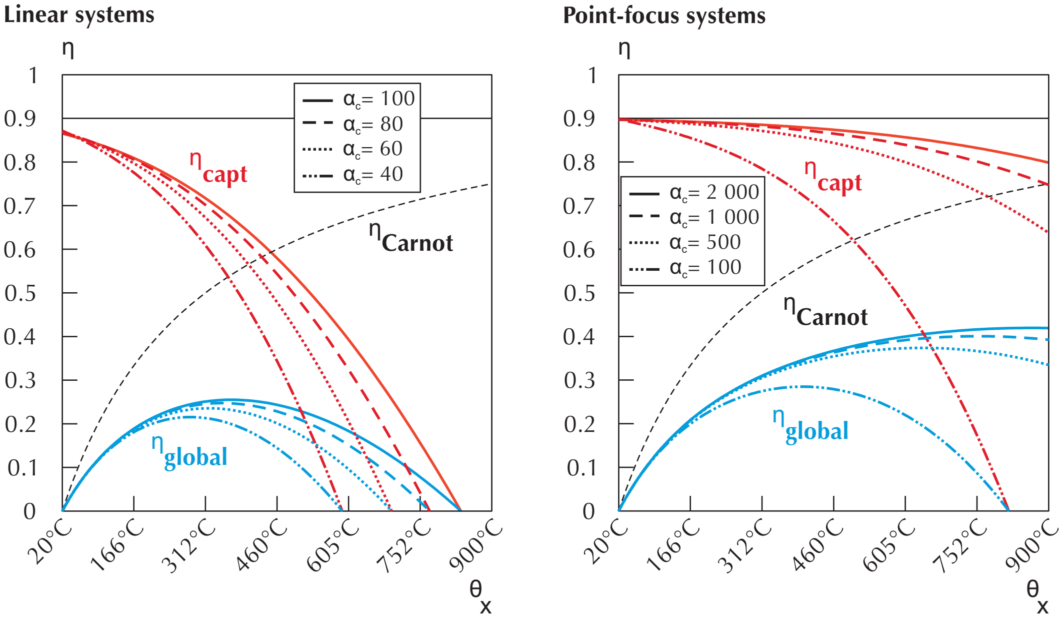
Parabolic troughs have been around for more than a century.

As Figure 8.1 shows, point-focus systems convert into electricity a larger fraction of the energy that falls on the receiver than linear systems. For each concentration level, there is an optimal temperature level – although this may change as receiver technology develops. The economic optimum might be significantly different from the efficiency-maximising value. In the case of concentration of 1 000 suns or above, moving from a temperature of about 800°C to about 1 000°C does not bring a considerable improvement in conversion efficiency but is likely to entail significantly higher costs for manufacturing the receivers and the thermodynamic engine.

Concentrating solar power plants

Solar thermal power plants are based on the technologies examined in Chapter 7 to capture the sun's energy as heat, notably troughs and towers, while Fresnel reflectors and dishes appear outsiders.

Figure 8.1 **Efficiencies as a function of temperature for various concentration ratios**



Notes: α_c= concentration ratio; θ_{capt} = the efficiency of the collector; θ_{Carnot} = the efficiency of the conversion of heat into electricity; θ_{global} = the global efficiency. Values are indicated for an ambient temperature of 20°C.

Source: Tardieu Alaphilippe, 2007.

Key point

There is an optimal working temperature for any given concentration ratio.

Parabolic troughs and linear Fresnel reflectors

All parabolic trough plants currently in commercial operation rely on a synthetic oil as heat-transfer fluid (HTF) from collector pipes to heat exchangers, where water is preheated, evaporated and then superheated. The superheated steam runs a turbine, which drives a generator to produce electricity. After being cooled and condensed, the water returns to the heat exchangers. Parabolic troughs are the most mature of the CSP technologies and form the bulk of current commercial plants. Investments and operating costs have been dramatically reduced, and performance improved, since the first plants were built in the 1980s. For example, special trucks have been developed to facilitate the regular cleaning of the mirrors, which is necessary to keep performance high, using car-wash technology to save water (Photo 8.2).

Most first-generation plants have little or no thermal storage and rely on combustible fuel as a firm capacity back-up. CSP plants in Spain derive 12% to 15% of their annual electricity generation from burning natural gas. More than 60% of the Spanish plants already built or under construction, however, have significant thermal storage capacities, based on two-tank molten-salt systems, with a difference of temperatures between the hot tank and the cold one of about 100°C.

Photo 8.2 **Cleaning of parabolic troughs at Ain Beni Mathar (Morocco)**

Key point

Reflective surfaces in STE plants need to be cleaned regularly.

Beyond incremental improvements in size, performance and costs, parabolic troughs would possibly experience more significant change if other heat transfer or working fluids could replace the synthetic oil, which limits the working temperatures to less than 390°C. The main options are:

- *water/steam*. Direct steam generation (DSG) in the collector fields would allow high working temperatures and reduce investment costs, as no heat-transfer fluid (HTF) and heat exchangers would be necessary. Work is needed to ensure the separation of water and steam, and handle the circulation of high-temperature, high-pressure working fluids, which is a challenge with mobile receivers. Furthermore, DSG does not lend itself to easy storage (see below);
- *molten salts*. This solution simplifies storage, as the HTF becomes the storage medium. Salt mixtures usually solidify below 238°C and are kept above 290°C for better viscosity, however, so work is needed to reduce the pumping and heating expenses required to protect the field against solidifying. The 5-MW Archimede plant in Sicily uses this technology developed by Italian government agency ENEA and Archimede Solar Energy. It is a solar fuel saver integrated in a larger natural gas plant;

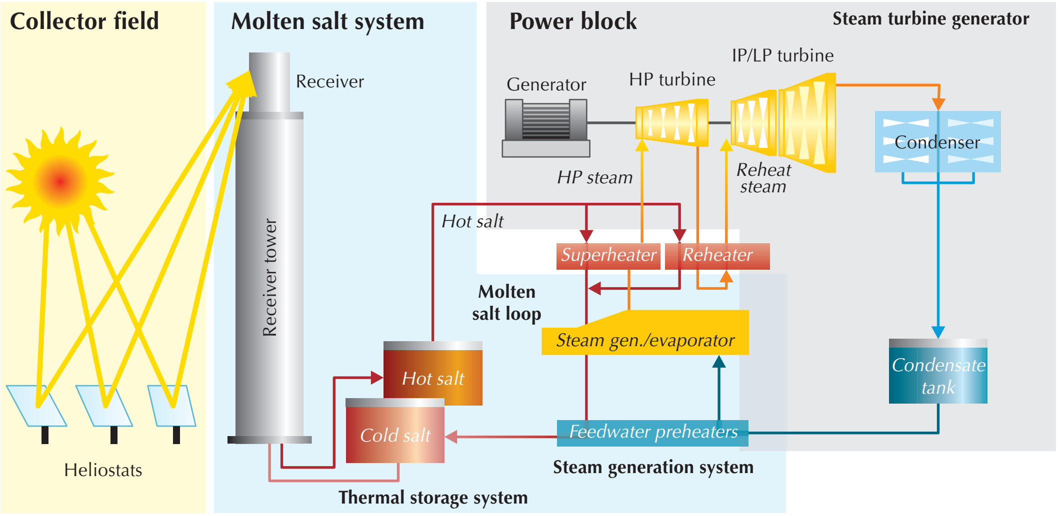
- *nano-fluids*. Dispersing solid particles in fluids enhances thermal conductivity, but particles rapidly settle in fluids. Nano-particles, possibly enhanced with surfactants/ stabilisers, would remain in suspension almost indefinitely, and have a surface area per unit volume a million times larger than that of micro particles, offering improved heat-transfer properties; and
- *pressurised gas*, currently under testing at the Plataforma Solar de Almeria, Spain. Additional work is needed to improve heat transfer in the receiver tubes, and to ensure control of the solar field, which is more complex than the standard design.

Linear Fresnel Reflectors could provide a lower-cost option, in particular for direct steam generation, thanks to fixed receivers and pipes. One weakness might be the greater cosine losses when the sun is low in the sky, which would tend to restrict electricity generation to the middle of the day.

Solar towers and dishes

Solar towers represent a less mature technology than trough plants. However, they hold the promise of greater efficiencies and ultimately lower costs than all other STE technologies, whether with or without storage. Some commercial tower plants now in operation in Spain and in construction in the United States generate the steam directly in the receiver. At least one other, in Spain, uses molten salts as both the HTF and storage medium. Others still may break ground in the United States (Figure 8.2). One advantage of using molten salts as HTF is that this can be done at low pressure with effective thin-wall solar receivers. Another is that it can avoid the investment and temperature differences of heat exchangers between the HTF and the storage medium.

Figure 8.2 **Working scheme of a molten-salt solar tower**



Source: SolarReserve.

Key point

Molten-salt towers represent the best option today for CSP with large thermal storage.

The high concentrating ratio (hundreds of suns) of the tower concept achieves high temperatures – 565° for molten salts, 550°C for the steam – thereby increasing the efficiency at which heat is converted into electricity. Improved efficiency also means a lower cooling load, thus reducing water consumption in plants in arid areas. It would also reduce the performance penalty of dry cooling. In addition, the concept is highly flexible; designers can choose from a wide variety of heliostats, receivers, transfer fluids and power blocks (some plants have several towers that form one power block). The potential for cost reduction in thermal storage is particularly impressive. Solar towers using molten salts as HTFs and storage media need three times less storage media than current trough plants, thanks to the larger temperature difference between the hot and cold molten salts.

The possibilities of even higher temperatures should be explored using different receiver technologies. One option is supercritical steam cycles, such as those used in modern coal-fired power plants, which reach overall efficiencies of 42 to 46% with supercritical and ultra-supercritical designs (thermal-to-electric efficiencies of 45% to 50%). Typically, modern coal-fired power plants use steam at up to 620 °C and 24 MPa to 30 MPa, but by 2020 could reach 700 °C and 35 MPa, using nickel-based alloys to achieve overall efficiencies approaching 50%. The application of this technology to solar towers, however, will require some adaptation.

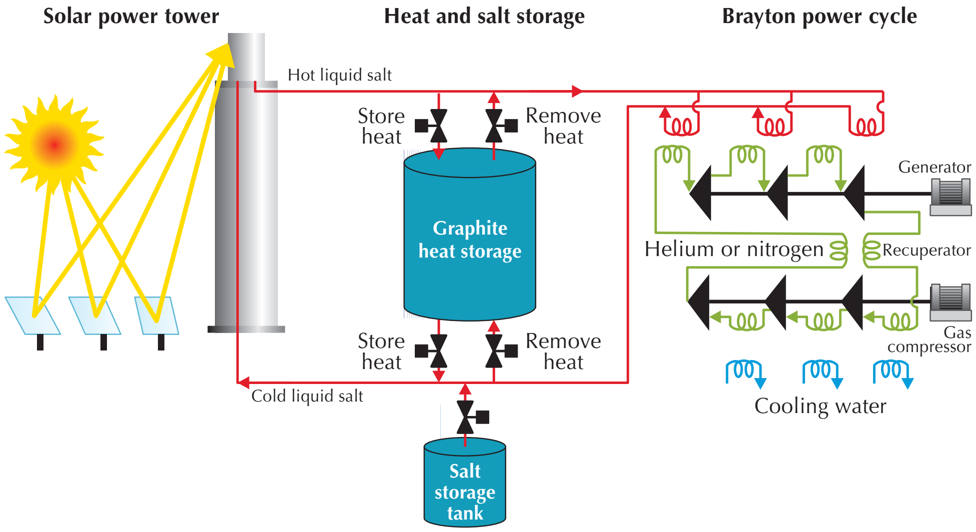
Direct steam generation (DSG) will pose particular challenges in synchronising solar fields with receivers and supercritical steam turbines. A continuous management of solar collectors will be needed to avoid problems during start-up and variations caused by clouds and at sunset. Solar towers with high-temperature HTFs and storage may prove more capable of fulfilling these requirements, as they disconnect solar heat collection and power generation. Superheating with some fuel, or full hybridisation in solar-gas or solar-coal plants (see below) could also help address these challenges. Solar towers would need to be paired to fuel each single supercritical turbine, whose minimum electric capacity today is 400 MW.

High-temperature tower concepts also include atmospheric air as the HTF (tested in Germany with the Jülich solar tower project) with solid material storage. Solar-to-electricity efficiencies of up to about 25% can be delivered by such towers, but it is not yet clear if the gain in efficiency may compensate for the cost and complication of the cycle.

Molten salts decompose at higher temperatures, while corrosion limits the temperatures of steam turbines. Higher temperatures and efficiencies could rest on the use of fluoride-liquid salts as HTFs up to temperatures of 700°C to 850°C, with closed-loop multi-reheat Brayton cycles using helium or nitrogen, which have initially been developed for high-temperature nuclear reactors (Figure 8.3). On top of higher plant efficiency, such power systems operate at relatively high pressure and power densities that implies smaller equipment than for steam cycles with their large low-pressure low-power-density turbines, so they could cost less. The preferred heat-storage medium in this case would be graphite.

Solar-based open Brayton cycles offer a completely different way of exploiting the higher working temperatures that towers can achieve. Pressurised air would be heated in the solar receivers, and then sent directly to a gas turbine, at a temperature exceeding 800°C. The pressurised air can be further heated in a gas fired combustion chamber to reach 1300°C, which makes the gas turbine more efficient. Excess heat after running the gas turbine could be sent to a steam cycle running a second generator. The solar-to-electricity efficiency could be higher than 30%. Heat storage, however, is still an unresolved issue for such plants, while fossil-fuel (or gasified biomass) back-up is more straightforward. Back-up fuel heating the air from the solar receiver could be used to manage solar energy variations, and if necessary continuously raise the temperature level. This concept was developed through the 100-kW Solgate project led by the German Aerospace Center (DLR), as illustrated on Figure 8.4. Pressurised air tube receivers were successfully tested in the middle 1980s in the German-Spanish GAST Technological project in Almeria reaching 850°C and 9 bars with metallic tubes and 1 100°C with ceramic ones. The 2-MW demonstration Pegase project set up by the French research centre CNRS will follow on the Themis solar tower in the Pyrenees. A more powerful 4.6-MW project along the same lines, Solugas, will run as a demonstration plant on a specially erected new tower at the Abengoa Solar test facility near Seville, Spain.

Figure 8.3 **Scheme of fluoride-liquid salt solar tower associated with a closed Brayton cycle**



Source: Forsberg, Peterson and Zhao, 2007.

Key point

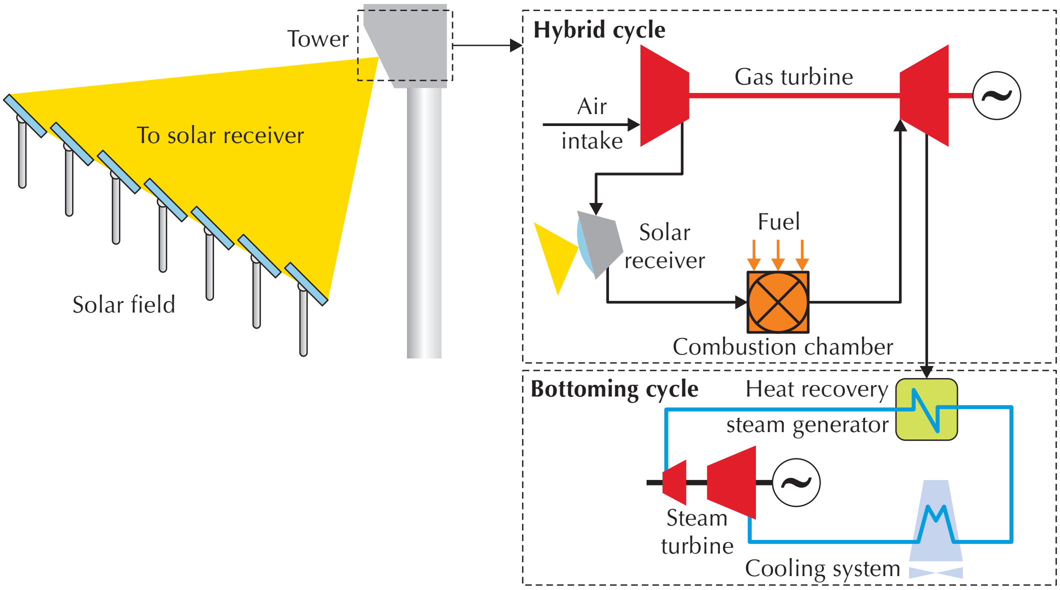
Solar towers may gain in efficiency with higher-temperature cycles.

Parabolic dishes offer the highest solar-to-electric conversion performance of any CSP system. Most dishes have an independent engine/generator (such as a Stirling machine or a micro-turbine) at the focal point. Several features – the compact size, absence of water for steam generation, and low compatibility with thermal storage and hybridisation – put parabolic dishes in competition with PV modules, especially concentrating photovoltaics (CPV), as much as with other CSP technologies. Very large dishes, which have been proven compatible to thermal storage and fuel back-up, are the exception. Promoters claim that mass production will allow dishes to compete with larger solar thermal systems. However, uncertainties relative to technology development and costs have so far prevented large projects in the hundreds of megawatts.

Balance of plants

As in other thermal power generation plants, CSP requires water for cooling and condensing processes. CSP water requirements are relatively high: about 3 000 L/MWh for parabolic trough and LFR plants (similar to a nuclear reactor) compared to about 2 000 L/MWh for a coal plant and only 800 L/MWh for combined-cycle natural gas plants. Dishes or Brayton cycle towers are cooled by the surrounding air with no need for cooling water.

Figure 8.4 **Concept of combined-cycle hybrid solar and gas tower plant with pressurised-air receiver**



Source: PEGASE/CNRS.

Key point

Small-scale air receivers for towers have been successfully tested.

Dry cooling (with air) is one effective alternative used on the ISCC plants in North Africa (Photo 8.3). Various dry cooling systems have been used for large fossil-fuelled steam plants in arid areas for at least 50 years, so maturity is not an issue. However, dry cooling costs more and reduces efficiencies by up to 7%.

There are other options, though. Hybrid wet/dry cooling systems reduce water consumption while minimising the performance penalty. For a parabolic trough CSP plant, this hybrid approach could reduce water consumption by 50% with only a 1% drop in annual electrical energy production. Another, more speculative option would be to build very tall cooling towers – of several-hundred-metre height. This concept, derived from the concept of "solar chimney" (see below), creates an up draft through the temperature difference between the air heated by the CSP plant, and the cold air at higher altitude. Originally thought as an independent means of generating electricity (the updraft would have flown through turbines), solar chimneys could simply cool solar plants, suppressing the need and costs of both air turbines and fans – and the parasitic electricity consumption of the latter (Bonnelle *et al.*, 2010).

Storage in CSP plants

Technologies for heat storage are described in Chapter 7. The current dominant technology for CSP plants is based on sensible heat in molten salts, whether for trough plants or solar towers. Increasing the overall working temperatures of plants is the best means of reducing storage costs. Adding nanoparticles to increase the heat capacity of molten salts or other liquid storage medium is another option (mentioned above), while phase change materials (PCMs) could be fixed inside the storage tanks with the same purpose. A third possibility is to use thermocline separation (change in temperate with depth) between hot and cold molten salts in a single tank, but leakage risks are more difficult to manage in this case.

Photo 8.3 **Dry cooling of the integrated solar combined cycle plant at Ain Beni Mathar, Morocco**

Key point

Dry cooling is a mature technology for steam plants in arid climates.

Storing the heat collected from the sun before generating electricity is much more efficient, with a round-trip efficiency in the 95% to 98% range, than storing electricity, for which the least costly option available on a large scale, pumped hydro, offers a round-trip efficiency of about 80%. Using thermal storage one needs to collect 2% to 5% more thermal energy if it goes to storage; as losses are only thermal, their cost is also lower as they do not imply running turbines in vain. Using electricity storage one needs to produce 25% more electricity if it needs to be stored.

Storage is a particular challenge in CSP plants that use DSG. Small amounts of saturated steam can be stored in accumulators, but this is costly and difficult to scale up. Effective full-scale storage for DSG plants is likely to require three-stage storage devices that preheat the water, evaporate the water and superheat the steam. Stages 1 and 3 would be sensible heat storage, in which the temperature of the storage medium changes. Stage 2 would best be latent heat storage, in which the state of the storage medium changes, using some PCM. Sodium nitrate ($NaNO_3$), with a melting temperature of 306°C, is a primary candidate for this function.

Thermal storage in STE plants can be used for a variety of purposes. The first objective is to make the capacities "firm" despite possible variations in the solar input. STE plants, especially linear designs with abundant HTF, already offer some thermal inertia, plus the spinning inertia of their turbines.

Thermal storage also allows shifting the production in time, usually on a daily scale. The idea is to produce electricity when it is most valued by utilities. This concept is all the more important when peak demand does not coincide, or coincides only partially, with the sunniest hours. Figure 8.5 illustrates the daily resource variations (DNI) and the flows from the solar field to the turbine and storage and from the field and storage to the turbine, in a CSP plant generating electricity from noon to 11 pm.

Thermal storage could also increase the capacity factor and achieve base load electricity generation, at least during most of the year. Alternatively, it could be used to concentrate the generation of electricity on demand peak hours.

Instead of adjusting the size of the solar field for different uses with the same electrical capacity, as is often suggested, the designers would more likely consider solar fields of the greatest possible size for large CSP plants inserted in grids, given the inherent optical limitations to heliostat field size (see Chapter 8) and the limitation of linear systems due to pumping losses through large fields. They would then adjust the turbine capacity to the possibilities of the solar field, serving different purposes, as illustrated on Figure 8.6.

At the top of Figure 8.6 (as on Figure 8.5) the storage is used to shift production from the sunny hours to the peak and mid-peak hours – say, noon to 11 pm. The solar field is thus roughly the same size as that of a CSP plant of the same capacity without storage[1] – which is expressed by a "solar multiple of 1". Such a design would likely fit the conditions of California. At the middle of Figure 8.6, the storage is used to produce electricity round the clock in a smaller turbine. This leads to a solar multiple greater than 2. Electricity is less costly this way, but has to compete with cheap base load power producing plants, usually coal or nuclear. At the bottom of Figure 8.6, the storage is used to concentrate the

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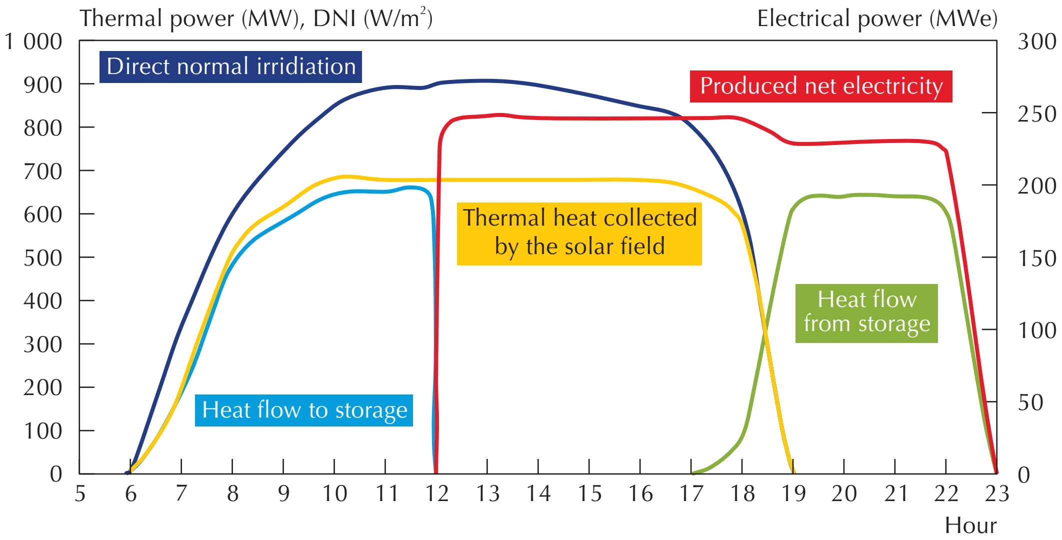
[1] *If a solar multiple of 1 is precisely defined as the size of the field that optimally feeds the turbine during the sunniest hour of the year, then a CSP plant without storage will in practice have a solar multiple of about 1.1 to feed the turbine during more hours, at the cost of small amounts of dumped energy.*

generation of electricity on the peak demand after sunset, with a larger turbine, which means a solar multiple smaller than 1. Electricity is more expensive in this configuration, but, if the power purchase prices duly reflect the marginal costs of alternatives, it might be the most profitable option. It would fit, for example, the condition of Morocco and South Africa.

Figure 8.5 **Firm and time-shifted production**



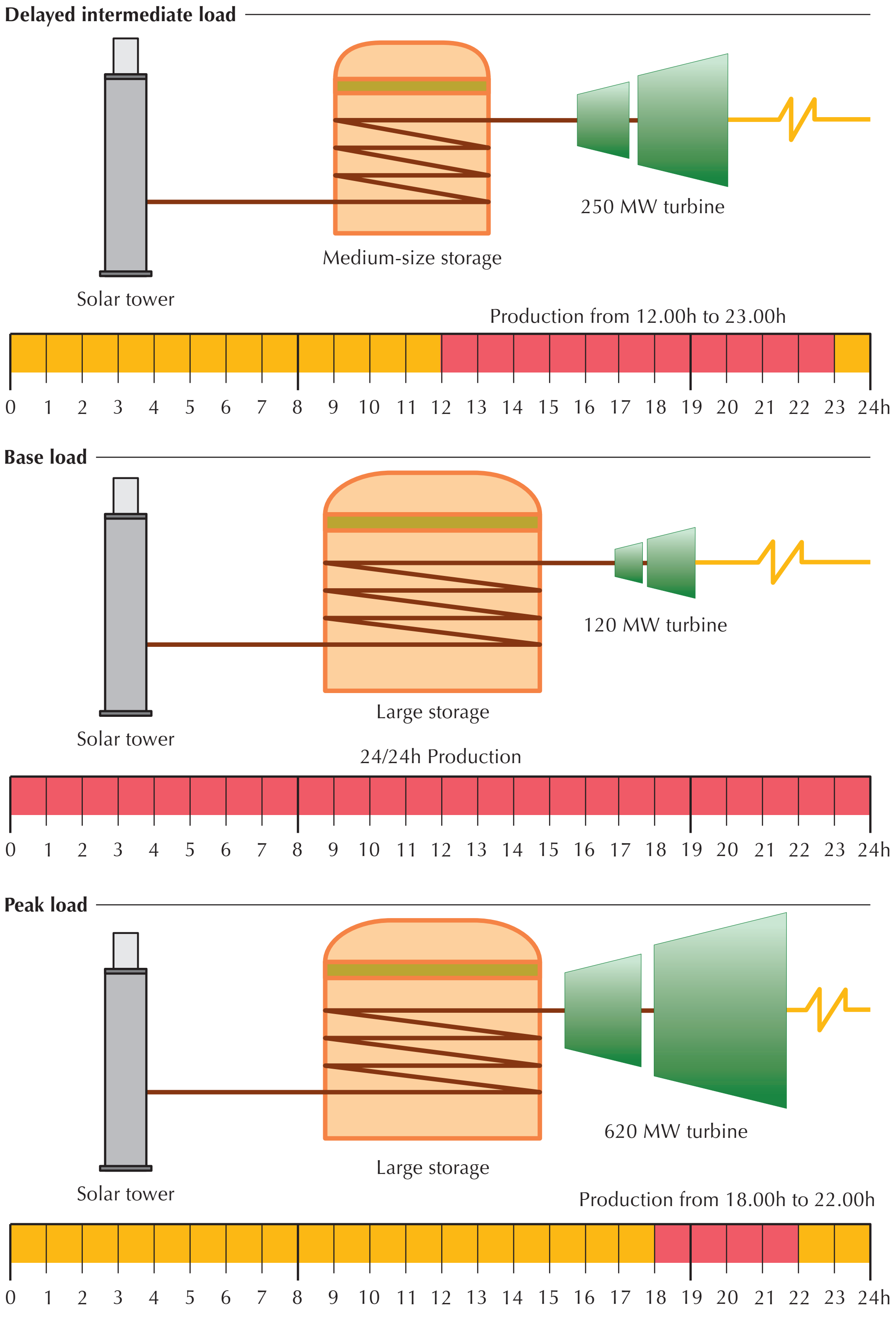
Source: ACS Cobra.

Key point

Thermal storage de-links solar energy collection and electricity generation.

Large storage capabilities, resting on high solar multiples (up to 3 or 4), would allow CSP plants to generate electricity round the clock, at least during most of the year, making it possible for low-carbon CSP plants to compete with coal-fired power plants that emit high levels of CO_2. For example, the 20-MW solar tower plant in Spain Gemasolar that was connected to the grid in May 2011 uses molten salts as both HTF and storage medium. It stores enough heat energy to run the plant at full load for 15 hours a day during most of the year. However, the economics of CSP suggest it is more profitable now to use storage to compete on peak loads where the incentives and/or market prices reflect the marginal cost of competitors in real time.

Figure 8.6 **Three different uses of storage**

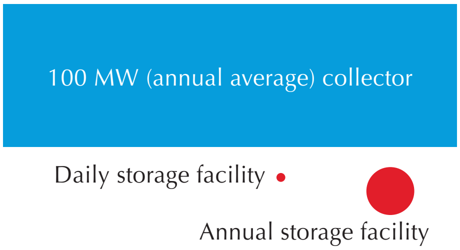


Key point

Thermal storage can shift, extend or concentrate the generation of electricity.

Seasonal storage for CSP plants would require much larger capacities still, and as noted in Chapter 7 it would more likely rest on stone storage, if it ever comes to fruition. The volume of stone storage for a 100 MW system would be no less than 2 million m^3, which is the size of a moderate gravel quarry, or a silo of 250 metre diameter and 67 metre high. This may not be out of proportion, in regions where available space is abundant, as suggested by the comparison with the solar collector field required for a CSP plant producing 100 MW on annual average on Figure 8.7.

Figure 8.7 **Comparison of the size of a 100 MW solar field and its annual 67-m high stone storage**



Source: Welle, 2010.

Key point

Annual thermal storage for CSP plants may emerge as a viable option.

Stones are poor heat conductors, so exchange surfaces should be maximised, for example, with packed beds loosely filled with small particles. One option is then to use gases as HTFs from and to the collector fields, and from and to heat exchangers where steam would be generated. Another option would be to use gas for heat exchanges with the collectors, and have water circulating in pipes in the storage facility, where steam would be generated. This second option would simplify the general plan of the plant, but heat transfers between rocks and pressurised fluids in thick pipes may be problematic.

Investment costs for annual storage would be less rapidly amortised than in the case of daily storage cycles, as it would in one sense provide service only once a year. On the other hand it would require very inexpensive storage media, such as stones; and the costs of heat exchangers, pumps and pipes would probably be much smaller per MW_{th} than for daily storage, as heat exchanges would not need to take place at the same speed. So annual storage may emerge as a useful option, as generation of electricity by CSP plant in winter is significantly less than in other seasons in the range of latitudes – between 15° and 35° – where suitable areas for CSP generation are found. However, sceptics point out the need for much thicker insulation walls as a critical cost factor.

There is another way to store the energy of the sun – thermo-chemical storage. In the case of low-temperature heat, as described in Chapter 7, the chemicals would probably remain inside some storage tank, and heat exchanges between the solar collectors and the storage tank will be done using some HTF. With high-temperature heat, however, the chemical reaction could take place in the receiver itself. This not only allows for storage, but the possibility of full dissociation in place and time of the collection of the solar energy and the generation of electricity. These options are considered in Chapter 9.

Back-up and hybridisation

Almost all existing CSP plants use some back-up fuel to substitute or complement thermal storage. Back-up helps to regulate production and guarantee capacity, especially in peak and mid-peak periods. The fuel burners (which can use fossil fuel, biogas or, eventually, solar fuels) can provide energy to the HTF or the storage medium, or directly to the power block.

Fuel burners also boost the conversion efficiency of solar heat to electricity by raising the working temperature level; in some plants, they may be used continuously in hybrid mode. For example, the 100-MW Shams-1 trough plant being built in the United Arab Emirates combines hybridisation and back-up, using natural gas and two separate burners. The plant will burn natural gas continuously during sunshine hours to raise the steam temperature (from 380°C to 540°C) for optimal turbine operation. This accounts for 18% of overall production of this peak and mid-peak plant. The plant will also have a HTF heater which guarantees capacity even at night. This back-up device was required by the electric utility and will be used only at its request to run the plant at night in case of contingency.

CSP can also be hybridised by adding a solar field to fossil fuel plants, whether existing plant or greenfield plants. Several schemes are conceivable, but only a few have been implemented. One option is to build a small solar field adjacent to a coal plant, pre-heating the feedwater. In coal plants, successive bleeds on the turbine subtract steam during its expansion in order to preheat the feedwater before it enters the boiler. The solar field can replace these bleeds, leaving more steam to be turned into electric power. One example of this is the 44-MW Cameo coal plant in Colorado, which added a 4-MW solar trough field in 2010.

A second option is to provide high-pressure steam to the bottom cycle of a combined cycle plant, in so-called integrated solar combined-cycle plants (ISCC). Several are in operation today in Algeria, Egypt, and Morocco (Photo 8.4) with capacities in the tens of megawatts (in equivalent electric capacities). The largest solar field added to an existing combined cycle power plant was recently built in Florida, with a capacity of 75 MW equivalent electric.

A more ambitious option is to provide high-pressure superheated steam for main steam augmentation, for example to a coal plant, possibly boosting the turbine for peak loads or simply substituting coal when solar resource is available. Such a scheme is currently being developed with the US Electric Power Research Institute on the 245-MW Escalante Generating Station in Prewitt, New Mexico. If the steam flux is made very stable thanks to storage and/or continuous hybridisation, solar heat could then benefit from the excellent conversion efficiency of the ultra-super-critical steam turbines used in modern coal plants.

As the solar share is limited, these schemes of hybridisation are a good means to displace fossil fuels. A positive aspect of solar fuel savers is their relatively low cost, especially when built adjacent to an existing plant. With the steam cycle, turbine, generators, balance of plant and connections to the grid already in place, only components specific to CSP require additional investment. This would likely prove the cheapest and fastest way to introduce significant solar shares into the electricity mix. Even without storage, fuel economy could be in the 20% to 30% range. With storage, it could go up to much higher levels. As explained above, this could also be the way to use super-efficient steam cycles to convert the solar heat into electricity.

Photo 8.4 **A parabolic trough and, reflected, the power block of the Integrated solar combined cycle plant at Ain Beni Mathar, Morocco**

Key point

CSP has entered North Africa as integrated solar combined cycle plants.

While for industrialised countries such schemes are more likely to take place on existing plants, insofar as the solar resource and available land permits, for developing countries it may also have a place on new-build plants. Although one might feel that hybrid plants are far from representing a definitive solution to GHG emissions, the reality is that some developing countries, including two giants – China and India – will remain largely dependent on coal to face their rapidly growing demand. Building solar-only plants sounds desirable, but if new coal plants are being built in the same area in the same timeframe, it might be preferable to built solar-coal hybrids. The same investment in solar fields would displace additional coal capacity and avoid increasing emissions, and the conversion of the solar energy into electricity would be more effective.

Smaller plants

For insertion into large grids, the optimal plant size seems to be in the 200 to 300 MWe range to benefit from scale effects; the most recent projects in the United States tend to target this range of capacities. Larger projects are made of several projects bundled together.

CSP technologies can also generate electricity on a smaller scale. Below 5 MW, however, steam Rankine turbines are usually replaced by organic Rankine cycle turbines, which have a greater efficiency in that power range. The first CSP plant built in the United States since the demise of Luz in 1991 was in 2005: the 1-MW Saguaro solar power plant in Arizona, where an organic fluid, pentane, replaces the usual water/steam working fluid.

Decentralised small plants might be particularly relevant for isolated or mini-grids on islands, remote rural areas or requiring connection to weak grids with insecure supply. They could also contribute to more developed grids in conjunction with generation of heat and/or cold for buildings (see Chapter 4), or process heat for industries and services (see Chapter 5). Small plants could be based on any of the CSP technologies – troughs, Fresnel, dishes and towers. Although the smaller size may suggest dishes would have a strong position in such applications, this is not necessarily the case as the added value of CSP, whether small or large, rests in its hybridisation and storage capacities. For example, the 30 m-high Aora Solar Tower in Israel uses a pressurised-air volumetric receiver and a standard jet-engine turbine to generate 100 kW electricity and 170 kW_{th} heat from the sun or biodiesel, natural gas or biogas (Photo 8.5).

Photo 8.5 **Small-scale solar tower in the Arava Desert, Israel**

Source: Boaz Dovev/Aora Solar.

Key point

Small CSP plants can provide dependable power to isolated villages.

Non-concentrating solar thermal power

Recent improvements in non-concentrating solar collectors, whether advanced flat-plate or evacuated tubes, make it possible to develop solar thermal electricity without concentration (although some collectors may incorporate low-concentration-level CPC devices). Highly efficient collectors could warm pressurised water to 130°C to 160°C (Photo 8.6). This heat could then run a thermal engine generating electricity. Solar-to-electric efficiencies would be low in comparison to CSP technologies, around 10% at best, which represents the lower end of PV efficiencies, but non-concentrating solar power could capture both direct and diffuse sunlight (like PV modules) and thus expand the geographic areas suitable for solar thermal electricity. In particular it might be suited to equatorial humid climates and sunny islands, where global irradiance is good but direct sunlight not so good.

Photo 8.6 **Experimental generation of electricity from non-concentrating evacuated tubes**

Source: SAED.

Key point

Non-concentrating solar thermal electricity uses diffuse and direct light.

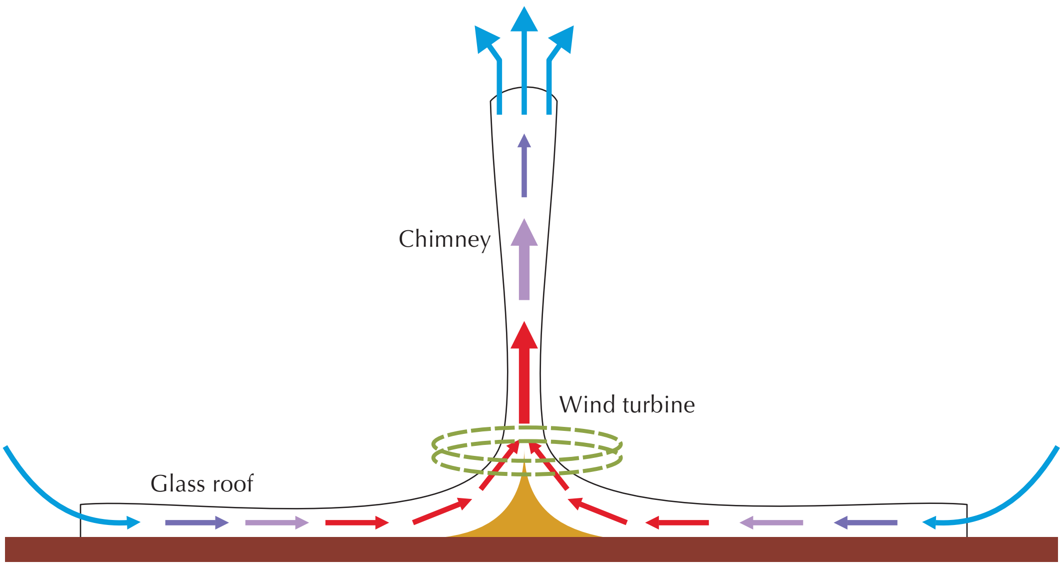
Relatively low-cost thermal storage and fuel back-up could make this technology a useful complement to PV, which is likely to remain less expensive for electricity generation in the sunniest locations. Another option would be to design systems integrating production of heat, possibly cold, and electricity, either altogether or with different outputs at different times of the year. Current experimental designs are based on turbines or micro-turbines using an organic mixture as heat transfer fuel, more appropriate than water for relatively low working temperatures. Engines with pistons and valves like the Ericsson motor could also be good candidates in this temperature range, but they are not manufactured on an industrial scale yet.

Another possibility is to use non-concentrating solar collectors to pre-heat feedwater of coal plants – as with concentrating systems though by necessity at a lower temperature. Here again, the advantage would be to save some fuel while using solar heat to produce electricity efficiently, with an investment limited to the solar field.

As mentioned above, solar chimneys or "up draft towers" could be used to create valuable air circulation through a tall chimney (one kilometre height or more) from a large greenhouse. The air flow would run turbines (Figure 8.8). The concept was tested small-scale in

Manzanares in Spain in the mid-1980s. It would use the shallow layer of the ground or simple water tanks in the greenhouse to level off the heat in the greenhouse and generate electricity around the clock. It is adapted to sunny countries even without high DNI, as no concentration of the solar resource is needed. The difficulty is that only very large systems would be economic, as the power output depends on the squared power of the dimensions. Therefore, moving from small-scale to mid-scale is uneconomic, while leapfrogging to large-scale seems risky. One possible way forward may be to first develop mid-scale up draft towers as dry cooling towers for CSP plants, avoiding having to bear the costs of the greenhouse, which have recently been suggested to be three to six times greater than those of the tall tower itself (Fluri *et al.*, 2009).

Figure 8.8 **Principle of a solar chimney**



Source: Schlaich and Robinson, 1995.

Key point

Solar chimneys need to be gigantic to be cost-effective.

Other solar thermal electricity technologies have been suggested. Solar thermoelectric generators could use the Seebeck or Peltier effects to generate electricity from heat – with no moving parts, as with PV systems. They need no sun-tracking device, as they need not concentrate the light of solar rays. Scientists at the Massachusetts Institute of Technology have recently achieved peak efficiencies of 4.6% with high-performance nano-structured thermoelectric material and spectrally-selective solar absorbers with high thermal concentration in an evacuated environment. This is still far from being able to compete with PV, but if it can be combined with heat storage it may open new avenues.

Costs of STE

For large, state-of-the-art trough plants, current investment costs are USD 4.2/W to USD 8.4/W depending on labour and land costs, technologies, the amount and distribution of DNI and, above all, the amount of storage and the size of the solar field relative to the turbine's capacity. Plants without storage that benefit from excellent DNI are on the low side of the investment cost range; plants with large storage and a higher load factor but at locations with lower DNI (around 2 000 kWh/m^2/yr) are on the high side.

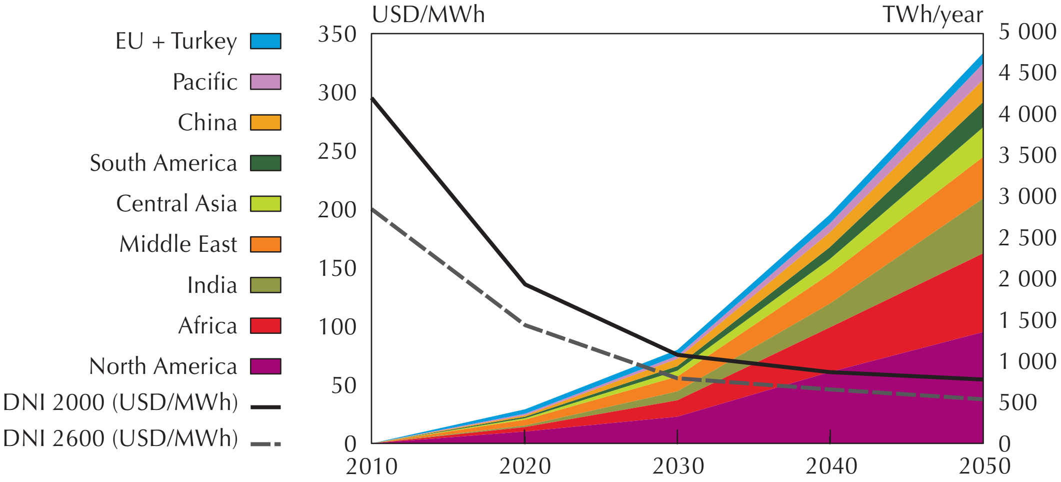
Investment costs per watt are expected to decrease with larger trough plants, going down by 12% when moving from 50 MW to 100 MW, and by about 20% when scaling up to 200 MW. Costs associated with power blocks, balance of plant and grid connection are expected to drop by 20% to 25% as plant capacity doubles. Investment costs are also likely to be driven down by increased competition among technology providers, mass production of components and greater experience in the financial community of investing in CSP projects. Turbine manufacturers will need to develop effective power blocks for the CSP industry. In total, investment costs have the potential to be reduced by 30% to 40% in the next decade.

For solar towers, investment costs are more difficult to estimate, but are currently higher than for trough plants. However, increasing efficiency from 15% to 25% will allow a 40% reduction in investment in solar-specific parts of the plants, or 20% of overall investment costs. The recent trend towards numerous mass-produced, small, flat mirrors promises to bring costs down further, as the problems of wind resistance and precision in directing the receptors is resolved using computers. As the solar tower industry rapidly matures, investment costs could fall by 30% to 75%.

The costs of CSP electricity could go down even more. Some experts see a greater potential in developing countries for local fabrication of towers than of troughs, leading to lower costs in emerging economies. In April 2011, a cost of only USD 140/MWh was offered by the winner of the tender for the first Chinese 50-MW CSP plant on a site in Inner Mongolia with DNI lower than 1700 kWh/m^2/year. Such an unusually low figure may reflect, beyond low labour costs and high local manufacturing content, exceptional financing conditions and the will to develop knowledge and experience even at a loss. India, too, is indicating sharp reduction in these costs – which would only be confirmed when the plants are up and running.

Assuming an average 10% learning ratio, CSP investment costs would fall by about 50% from 2010 to 2020, as cumulative capacities would double seven times, according to the *IEA Technology Roadmap: Concentrating Solar Power* (Figure 8.9). Electricity costs would decrease even faster thanks to progressively greater capacity factors, making CSP technology competitive with conventional technologies for peak and intermediate loads in the sunniest countries by about 2020.

Figure 8.9 **Decreasing costs and increasing CSP production**



*Source: IEA, 2010*d.

Key point

STE from CSP plants will be competitive by 2020 for peak electricity generation.

Photo 8.7 **Partial view of the solar field of a CSP plant**

Source: Corbis Images.

Key point

Most concentrating solar power plants in service today use parabolic troughs.

Chapter 9
Solar fuels

Solar energy can be used to generate hydrogen from water electrolysis or various processes based on water or any hydrocarbon, and concentrated solar heat. Hydrogen can be used as such or to further process other fuels, notably convenient liquid fuels. For liquid fuels, which normally contain carbon atoms, the preferred option from a climate point of view is solar-enhanced bio-fuels.

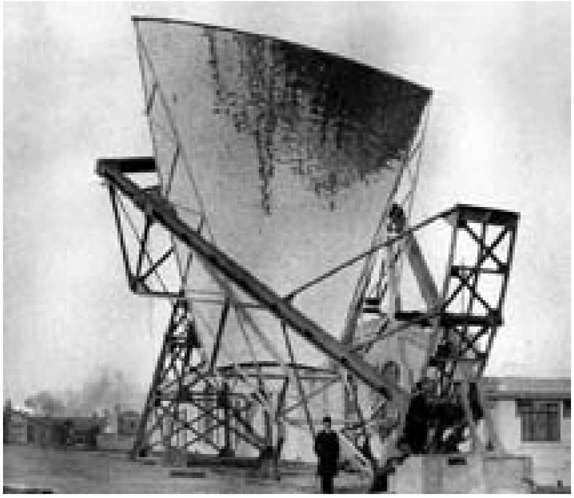
Background

In 1904, Manuel Gomez, a Portuguese Jesuit nicknamed Padre Himalaya, aiming at synthesising fertilisers, obtained a temperature of 3 800°C from concentrating sunrays in his 'Pyreheliophoro' (Photo 9.1).

In the last 20 years, scientists in Europe, Israel, Japan and the United States have been working on gaseous, liquid or solid "solar fuels" manufactured from carbonaceous feedstock or water.

In 2011, in his State of Union speech, President Obama alluded to solar fuels: "At the California Institute of Technology, they're developing a way to turn sunlight and water into fuel for our cars."

Photo 9.1 **Padre Himalaya's Pyreheliophoro in 1904**



Source: Collares Pereira.

Key point

Solar fuels were first considered more than a century ago.

Carbon and hydrogen

As noted in Chapter 1, fossil fuels are remnants of ancient living organisms, which drew their energy from the sunlight through photosynthesis, associating carbon atoms taken from the air in carbon dioxide (CO_2) molecules, and hydrogen atoms taken from water, building hydrocarbon chains and releasing oxygen. These hydrocarbon chains carry the energy of biomass, natural gas, oil and coal.

Some scientists are seeking to mimic photosynthesis and directly generate hydrocarbon chains with water and CO_2 under sunlight. Using living organisms to capture solar energy through photosynthesis is generally considered "biomass", not direct solar energy. Recent developments however, such as the first facility converting CO_2 captured from a nearby cement factory into synthetic liquid fuel using microscopic algae and sunlight, evokes an "industrial solar plant" rather than a plant (Photo 9.2). Its economics are based on the sales of fatty acids to the agro-food industry, a "by-product" which is more highly valued than the main product, synthetic oil.

Photo 9.2 **Near Alicante, Spain, tubes filled with microscopic algae turn CO_2 and sunlight into synthetic oil**

Source: BSF Blue Petroleum.

Key point

Micro-algae are expected to produce fuels and high-value products in bio-refineries.

"Solar fuels" could have many forms, mainly gaseous or liquid. Gaseous solar fuels could be pure hydrogen, or a mix of hydrogen and methane (CH_4). Liquids are much easier to handle than gases or solids, especially in transportation. To be liquid at normal (atmospheric) pressure, however, most fuels need carbon atoms, so they would be hydrocarbons. Producing liquid fuels from solar requires some carbonaceous feedstock. In practice, it is possible to make solar gas-to-liquid or solar coal-to-liquid fuels and, of course, solar biomass-to-liquid. One could also use CO_2 streams, for example captured (but not stored) in the exhaust gases of a large combustion facility such as a power plant. If one uses gas or coal, or even biomass, solar energy is not required. Some liquid fuels are already produced, for example, in the Middle-East and in the Republic of South Africa, from gas or coal. Biofuels represent a growing global industry, providing about 2% of the global demand for liquid fuels for transport – 3% of road transport fuels.

Solar pyrolysis or gasification of biomass would greatly reduce the CO_2 emissions involved in the manufacturing of biofuels. Alternatively, solar processing of the biomass could be seen as a way to increase the available energy from a given biomass feedstock, avoiding the use of significant share of this feedstock as energy input into the process.

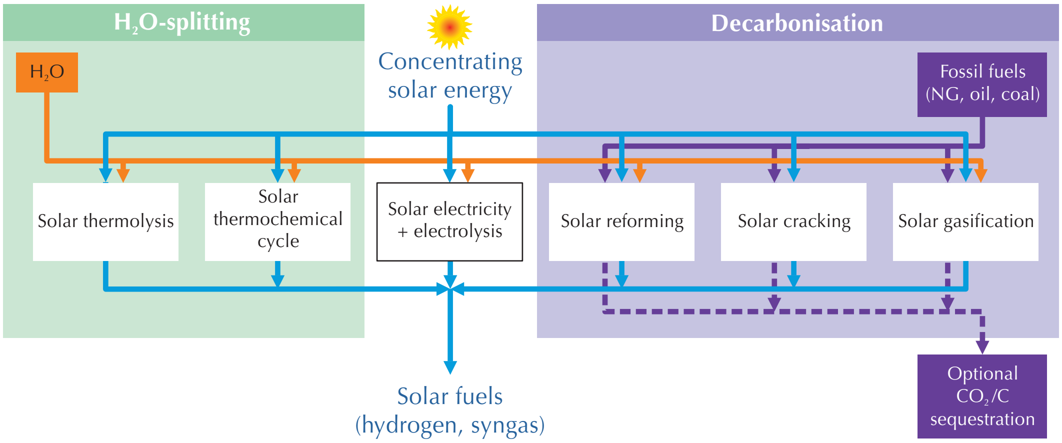
When solar liquid fuels are burnt, *e.g.* in the internal combustion engine of a car or other vehicle, their carbon atoms are oxidised, generating CO_2 emissions. Nevertheless, using solar as the energy source for the process saves fuel, as a significant share – perhaps one-third on average – of the initial energy content of the fuel, whether fossil or biomass, is consumed during the fuel manufacturing process. This also entails significant CO_2 emissions. When the initial fuel is coal, upstream emissions are even greater than end-of-pipe emissions when the fuel is burnt. Therefore, if using liquid solar fuels provide only limited climate change mitigation benefits compared to petroleum products, they accomplish a lot when compared to ordinary coal-to-liquid fuels. In the "Reference" scenario of *ETP 2008* and *ETP 2010*, there is a sharp increase in CO_2 emissions after 2030 due to the introduction of large amounts of coal-to-liquid fuels as substitutes for oil products. Although in scenarios with lower fossil fuel consumption, keeping fossil fuel prices lower, there would be less coal-to-liquid manufacturing, it would be very useful to produce such fuels with little or no upstream emissions by substituting solar heat for the coal energy combusted in the manufacturing process. If natural gas is reformed with CO_2 which was separated from flue gas of a power plant, the final product will have half of its carbon atoms from recycled CO_2.

Producing hydrogen

Solar fuels are usually made from hydrogen. Hydrogen can be produced by electrolysing water, and if the electricity is of solar origin, it can be considered "solar hydrogen". Producing solar hydrogen via electrolysis of water using solar-generated electricity offers an overall solar-to-hydrogen efficiency of about 10% with current technologies. Heating the water before it gets electrolysed is an effective means of reducing the required amount of electricity, and this too can be done with solar energy, thereby increasing the efficiency of the conversion of electricity into hydrogen. However, it is unclear when and where hydrogen really has to be preferred to electricity as an energy carrier (see Chapter 5), so the remainder of this chapter focuses on another way of producing hydrogen from solar energy – concentrating solar thermal technologies.

Concentrating solar technologies allow producing hydrogen, either from pure water, or from a carbonaceous feedstock, following various routes (Figure 9.1). Solar towers are the most obvious candidates to deliver the required high-temperature heat, but large dishes and, in some cases, line-focus technologies could also be used. The theoretical maximum efficiency of such an energy conversion process is limited only by the Carnot efficiency of an equivalent heat engine: with the sun's surface as a 5 800°K thermal reservoir and the earth as the thermal sink, 95% of the solar energy could in principle be converted into the chemical energy of fuels. In practice, however, lower temperatures will be used for material constraints.

Figure 9.1 **Routes to hydrogen from concentrating solar energy**



Source: PSI/ETH-Zürich.

Key point

Solar hydrogen can be produced from hydrocarbons or water.

Solar-assisted steam reforming of natural gas, and steam gasification of coal or solid biomass, can yield syngas, a mixture of carbon monoxide (CO) and hydrogen. This route is certainly the closest to commercialisation, as steam reforming of natural gas today is the primary route to producing hydrogen for industrial purposes (mostly manufacturing of ammonia and fertilisers, and desulphuration of petroleum products). The natural gas is used as both energy source and feedstock. Replacing natural gas as the energy source saves some gas and reduces CO_2 emissions. The carbon monoxide can be further processed to give H_2 and CO_2. The latter can be easily separated from the former via pressure swing adsorption[1], while CO_2 mixed in exhaust gases requires more energy and reactants to be captured. However, liquid transportation fuels, as well as methanol or ammonia, can also be manufactured directly from syngas using commercially available Fischer-Tropsch processes. Solar-assisted steam reforming of natural gas can be done at about 850°C, a temperature easily accessible to point-focus concentrating solar devices. Newly-developed catalytic membrane reformers can operate at only about 550 to 600°C, making it accessible to the lower concentration factors

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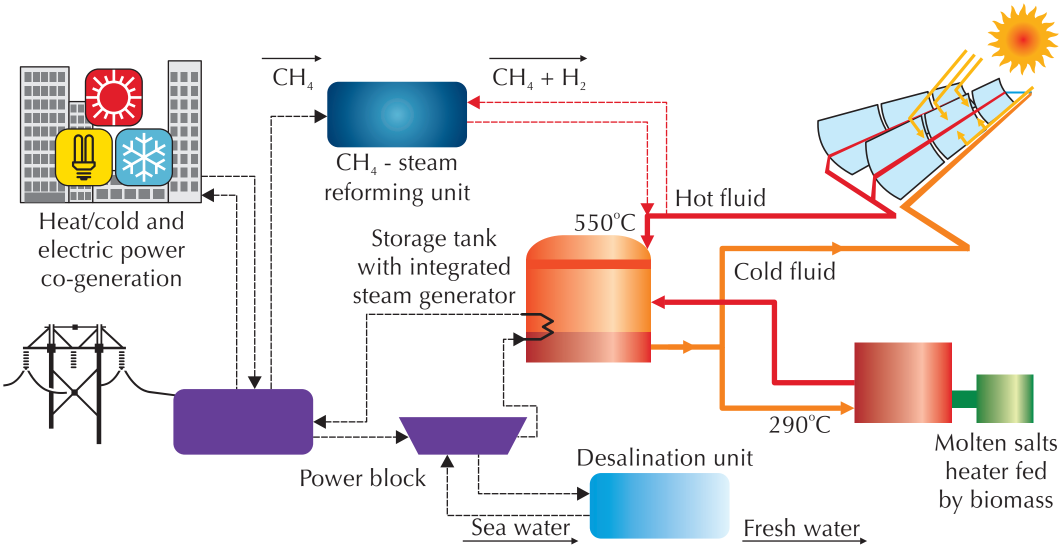
[1] *Pressure swing adsorption is a technology used to separate some gas species from a mixture of gases under pressure according to the species' molecular characteristics and affinity for an adsorbent material.*

in line-focus systems such as trough plants using molten salts as both storage medium and HTFs. This is currently being developed by ENEA in Italy (Figure 9.2).

Figure 9.2 **CSP backed by biomass could produce electricity, heat or cold, hydrogen and fresh water**



Source: ENEA-UTRINN-STD.

Key point

Solar fuels can be generated in parallel with electricity and freshwater.

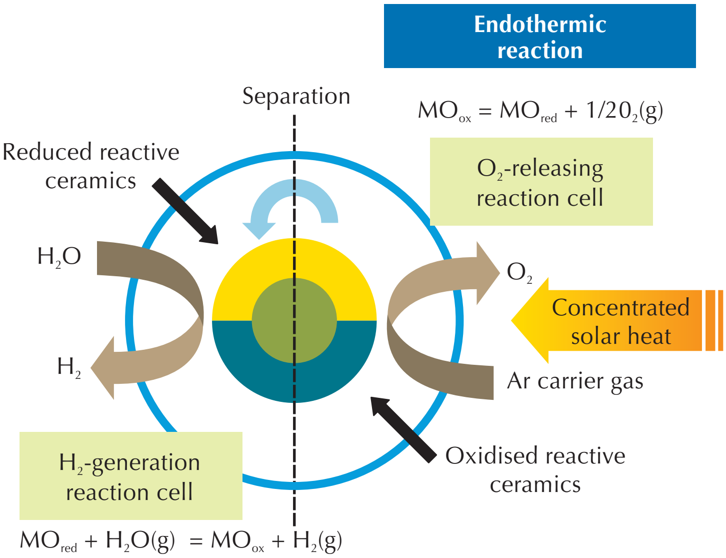
The production of pure hydrogen from water or from both water and biomass would be considered a superior form of solar hydrogen since it is based on an extremely abundant and fully renewable resource (hydrogen is recombined in water when used as a fuel) with no CO_2 emissions. It requires, however, much more research.

Solar thermolysis requires temperatures above 2 200°C, and raises difficult challenges. Water-splitting thermo-chemical cycles allow operation at lower temperature levels (some less than 1 000°C). But they require several chemical reaction steps, and there are inefficiencies associated with heat transfer and product separation at each step. Thermal cracking of natural gas will directly produce hydrogen and marketable carbon black. These options too require long-term research efforts.

More efficient two-step cycles using reversible reduction-oxidation (redox) reactions can also be used. This can take place, for example, in rotary kilns, as shown on Figure 9.3. Reduced reactive ceramics or metals are oxidised by water, generating H_2. The oxidised ceramics are then exposed to concentrated solar heat and release O_2.

The two steps of splitting water, instead of taking place at the focus of a concentrating solar tower, could also be separated in time and place, offering interesting possibilities for their use in transportation. Dedicated concentrated solar fuel plants would de-oxidise light elements, which would be easily transported to customer stations or even within vehicles, where their oxidation with water produces hydrogen (and heat). Oxides are then returned to the solar plants. Aluminium, magnesium and non-metallic elements such as boron are good candidates as energy carriers in such schemes, although zinc seems to offer the best properties for efficient reduction in solar receivers. These solar fuels will thus be solids, easier to store and transport than gases, while not intended to being used as solids when final, useful energy is to be delivered.

Figure 9.3 **Two-step water splitting based on redox reactions generating H_2 from sun and water**



Note: M = metal.

Source: Tamaura, Kaneko et al.*, Solutions Research Laboratory, Tokyo Institute of Technology.*

Key point

Small-scale production of solar hydrogen from water has been demonstrated.

This way of carrying and storing hydrogen and its huge energy content per unit of mass is likely to be more effective than compressing or liquefying hydrogen, both processes entailing important energy losses. If oxidation does not take place in cars and planes, it could take place in refuelling stations or larger plants and serve road and maritime transportation, as well as some industrial uses. In fact, the products are metals which are usable as fuels to generate either high-temperature heat via combustion or electricity via fuel cell and batteries (for example, zinc-air batteries), or to generate hydrogen and use it in various forms.

As scientists from the Paul Scherrer Institute Aldo Steinfeld and Robert Palumbo note, *"hydrogen can be further processed to make other fuels or it can be used directly for producing electricity or other forms of power. Once the hydrogen is expended, it will convert* *back to water…. you notice a cyclic process. No material is consumed. No material is discharged. The only energy that enters into the process is sunlight. The energy available in the hydrogen used to produce electricity or power is solar energy in disguise."*

However, research suggests the process is made easier, and the required temperature lowered (but still above 1 200°C) if some natural gas is also used in the process, again not as an energy source but as a reactant to reducing the zinc oxide and providing syngas. Solar chemical reactor prototypes have been tested and developed further at the Paul Scherrer Institute in Switzerland and Weizmann Institute in Israel. Other "redox" cycles have been tested, and some require lower temperature levels, such as the tin dioxide carbon reduction (900°C). Then again, liquid fuels could be manufactured with carbon atoms.

Solar-enhanced biofuels

As most liquid fuels require carbon atoms, the more climate-friendly option would be gasification or pyrolysis of biomass in concentrating solar towers, using CO_2 captured from the atmosphere by the plants. This would reduce the land and water requirement of current or future (advanced) biofuels, as concentrating solar in sunny countries is more land-efficient than burning part of the biomass in providing high-temperature process heat. Indeed, one company in Colorado has already tested the technology on a small scale: Sundrop Fuels, a spin-off of the US National Renewable Energy Laboratory. Cellulosic biomass of any kind was almost instantaneously gasified at temperatures above 1 100°C on a solar tower (Figure 9.4). At this temperature level, no volatile hydrocarbon tar was produced[2] (Perkins and Weimer, 2009). The resulting syngas could then be turned into any kind of liquid fuels through Fischer-Tropsch or other similar processes, with properties quite close to those of petroleum products As natural gas is currently cheaper, the company is using it as the energy source for its first large-scale biofuel plant. Concentrating solar heat or electricity remain options for the future deployment of advanced biofuels.

It is probably too early to tell if this particular technology, which has been demonstrated on a small scale, can be scaled up with sufficient efficiency. Sceptics note that advanced biofuels using any type of cellulosic material are not yet fully mature technologies, and believe that solar heat would add to the cost and complications. Others insist that the advantage of high-temperature solar heat with no combustion residues will, to the contrary, help overcome the current difficulties in developing advanced biofuel technologies.

There are other options. For example, solar distillation of ethanol reduces the consumption of fossil fuel in the manufacturing of standard 1st generation biofuels and has likely reached competitiveness with oil prices by now, *e.g.* in Thailand (Vorayos *et al.*, 2006). Similarly, the torrefaction of raw biomass – a mild form of pyrolysis at temperatures ranging between 200-320°C – to make it a more energy-dense, cleaner, hydrophobic and stable solid fuel,

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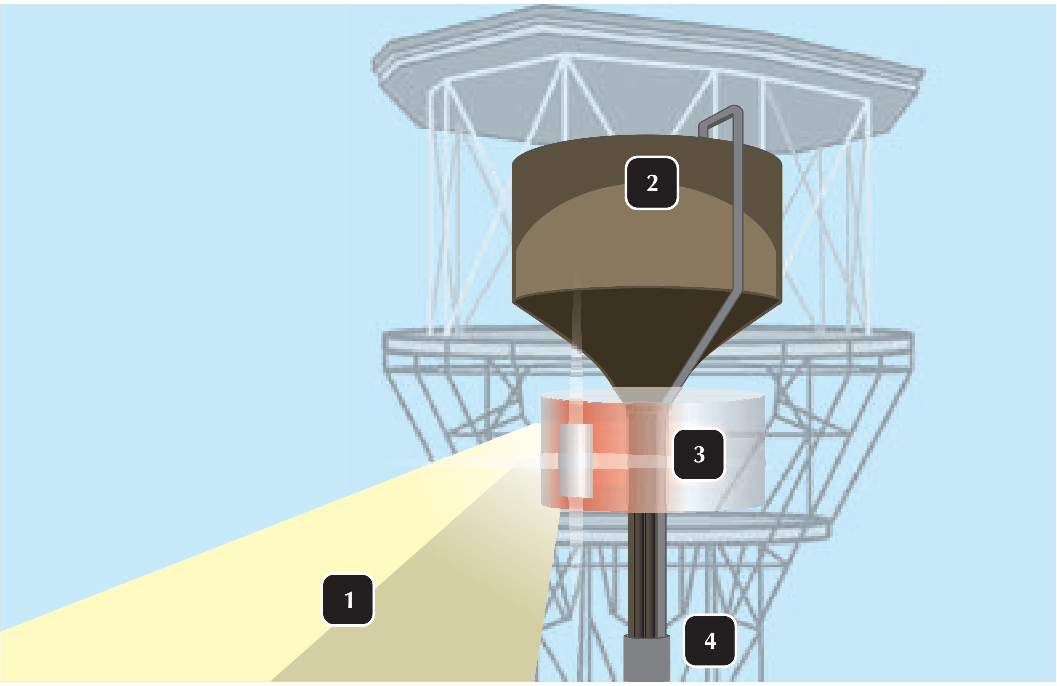
[2] Tar production during gasification driven by burning biomass (or natural gas) at temperatures below 1 000°C is one of the main difficulties in manufacturing advanced biofuels. It causes fouling of downstream catalytic surfaces and clogging of processing equipment.

sometimes called "bio-coal", could possibly benefit from using solar energy as a heat source. The process is sometimes claimed to be self-sustained, as the torrefaction produces the emission of gases, notably carbon monoxide (CO) and hydrogen (H_2), thus some sort of syngas, which is being burnt to generate the middle-temperature heat (200°C to 300°C) that sustains the process. Other sources suggest a few percent of the solid output needs to be burnt in the process. In both cases, if solar heat is introduced to run the process, the desired output would be increased, as would the possibilities of valuing the syngas generated together with the bio-coal.

Figure 9.4 **Solar-driven biomass gasification**



Notes: 1. Concentrated solar power from heliostats on the ground is directed into the thermochemical reactor on top of a tower. 2. Finely ground biomass is delivered by pneumatic tube into a feeder unit above the reactor. 3. Feedstock is dropped through the reactor's solar furnace, where temperatures of 1300°C gasify the material. 4. Syngas is collected and delivered to the adjacent biorefinery to create green gasoline or diesel fuels.

Source: Sundrop Fuels, Inc.

Key point

Solar heat can gasify biomass and increase biofuel production.

Using solar fuels

Solar thermal hydrogen production costs are expected to be USD 2/kg to USD 4 /kg by 2020 for efficient solar thermodynamic cycles, significantly lower than costs of solar electricity coupled with electrolysis, which are expected to be USD 6/kg to USD 8/kg when solar electricity cost is down to USD 80/MWh. Solar-assisted steam reforming of natural gas would become competitive with natural gas (as an energy source) at prices of about USD 11 /MBtu.

Solar gasification of biomass, if syngas is further converted into CO_2 and hydrogen, could possibly offer the cheapest non-fossil option, benefitting from the energy content of both the solar flux and the biomass.

Hydrogen from CSP could be used in today's energy system by being blended with natural gas. Town gas, which prevailed before natural gas spread out, included up to 60% of hydrogen (in volume), or about 20% in energy content. This blend could be used for various purposes in industry, households and transportation, reducing emissions of CO_2 and nitrous oxides. Gas turbines in integrated gasification combined cycle (IGCC) power plants can burn a mix of gases with 90% hydrogen in volume.

Solar hydrogen could also find niche markets today in replacing hydrogen production from steam reforming of natural gas in its current uses, such as manufacturing fertilizers and removing sulphur from petroleum products.

One of the major uses of hydrogen in industry today is the desulphuration of oil. Regenerating hydrogen with heat from concentrated sunlight to decompose hydrogen sulphide into hydrogen and sulphur, could save significant amounts of still gas in refineries for other purposes.

Coal could be used together with gas as feedstock, and deliver dimethyl ether (DME). One molecule of methane, one molecule of carbon (coal) and two molecules of water would be recombined as two molecules of DME, after solar-assisted steam reforming of natural gas, coal gasification under oxygen, and two-step water splitting. This scheme is currently being considered in China for coal liquefaction as some of the coal-richest Chinese regions such as Qinghai, Xinjang, Shaanxi and the Ordos area in Inner Mongolia offer enough direct normal irradiance for concentrating solar power. DME could be used as a liquid fuel, and its combustion would entail similar CO_2 emissions to those from burning conventional petroleum products, but significantly less than the life-cycle emissions of other coal-to-liquid fuels.

Solid and liquid biofuels enhanced from solar heat could be used in virtually all transport and industry applications.

PART C
THE WAY FORWARD

Chapter 10
Policies

An integrated approach to solar energy needs to consider all solar technologies and how they intersect with others, and the policies relevant to different stages of technology and market maturity. Identifying the policy needs, and designing the policy tools that will give policy makers in 10 and 20 years from now a broad choice of affordable and sustainable energy technologies, is currently the most pressing objective.

This chapter focuses on the important issue of the economics and financing of the early deployment of not-yet-competitive solar technologies, and related policy needs. The first section considers the costs of support schemes from a broad perspective. It aims at making clearer what, in most support schemes, is "normal" payment for energy, and what could be termed subsidy, or learning investment. The second section discusses the various support schemes, market designs and CO_2 pricing.

The costs of early deployment

Solar electricity, whether from PV or CSP, is not yet competitive with most other electricity generating technologies and energy sources. Its current deployment – called "early" for this reason – is essentially driven by incentives.

Support incentives reflect the willingness of an ever greater number of governments and policy makers to broaden the range of energy technology options with inexhaustible, clean renewable energy sources. They drive early deployment, which in turn drives learning and cost reductions. Long-term benefits are expected to be considerable, from climate change mitigation to other reduced environmental impacts, reduced price volatility and increased energy security. Short-term costs, however, raise concerns among policy makers. In the last few years, drastic policy adjustments have affected PV in European countries and the financial sustainability of its unexpected rapid growth, driven by production incentives and unexpectedly rapid price declines.

Debates among policy makers on the costs of support schemes are unlikely to disappear from the agenda anytime soon. At the end of 2010 existing PV commitments, usually extending to 15 or 20 years, represented yearly amounts of USD 7.6 billion in Germany, USD 3.6 billion in Italy, USD 2.8 billion in Spain and USD 0.8 billion in both France and the Czech Republic. Except in Spain, where the public budget is liable, these costs are passed-on to ratepayers.

The accumulation of financial liabilities due to support policies to solar electricity must be fully understood. For example, the current cumulative PV capacity is 40 GW, the next additional 40 GW would likely bring system costs from USD 3/W at present down to USD 2.55/W on the basis of a learning rate of 15% for utility-scale PV systems. The total investment would be about USD 111 billion.

What would be the "subsidy" part of the overall cost of incentives? A worst-case scenario would consider a market value of only USD 1/W, at which level PV electricity is competitive in most countries, including not so sunny ones. In this case, the overall investment is worth

USD 40 billion and the "subsidy" part of the incentive system is USD 71 billion. One can thus compute the total undiscounted amount of investment required to bring PV systems to competitiveness, using several simplifications[1] and following these worst-case assumptions, at about USD 6 350 billion. However, the real cost of support policies, *i.e.* the amount of incentives needed to fill the gap between the cost of PV and that of competitive technologies, would be lower at USD 1 266 billion, or about 5 times less (Table 10.1).

Table 10.1 **Amounts of investment bringing PV costs to USD 1/W (worst-case scenario)**

Additional capacity (GW)	Cost target (USD/W)	Total cost (USD bn)	Cumulative capacity	PV support (USD bn)	Cumulative investments*	Cumulative support costs*
40	2.55	111	80	71	111	71
80	2.17	189	160	109	300	180
160	1.84	321	320	161	621	341
320	1.57	545	640	225	1 166	566
640	1.33	927	1 280	287	2 093	853
1 280	1.13	1 576	2 560	294	3 669	1 147
2 560	0.96	2 679	5 120	119	6 348	1 266

*Notes: All costs are undiscounted. * Not taking account of the sunk costs of the current 40 GW basis.*

The oversimplifying assumption used here of a unique break-even point as a worst-case scenario differs from reality. As this publication shows, solar electricity (whether PV or CSP) is already competitive in some markets, and will be soon in much larger ones. Solar electricity is competitive off grid, whether for rural electrification, telecommunication relays or isolated houses. Rooftop PV is close to grid parity in several markets (for example if PV systems are installed in Italy at the price they are installed today in Germany).[2] PV and CSP plants are close to fuel parity at peak demand times. In sunny regions, when oil products are burned at demand peaks, PV or CSP plants are competitive when oil prices are above USD 80/bbl. These are not "niche markets" anymore, as telecommunication relays and rural electrification might have been at the end of the last century. Rather, they are leading or opening markets with a value measured in billions. Any sound, global deployment strategy needs to make support incentives as cost-effective as possible, as is considered in the next section. It must also build on these leading markets, so the costs of subsidies will remain considerably lower than the trillions of US dollars referred to above.

Nevertheless, in scaling up, investment costs always increase, as a doubling in cumulative capacity is necessary to get a 15% unit cost reduction. If incentive mechanisms entirely finance these investments, they would make the overall amount of subsidies appear to be continually growing even when unit costs approach competitive levels. It is important to

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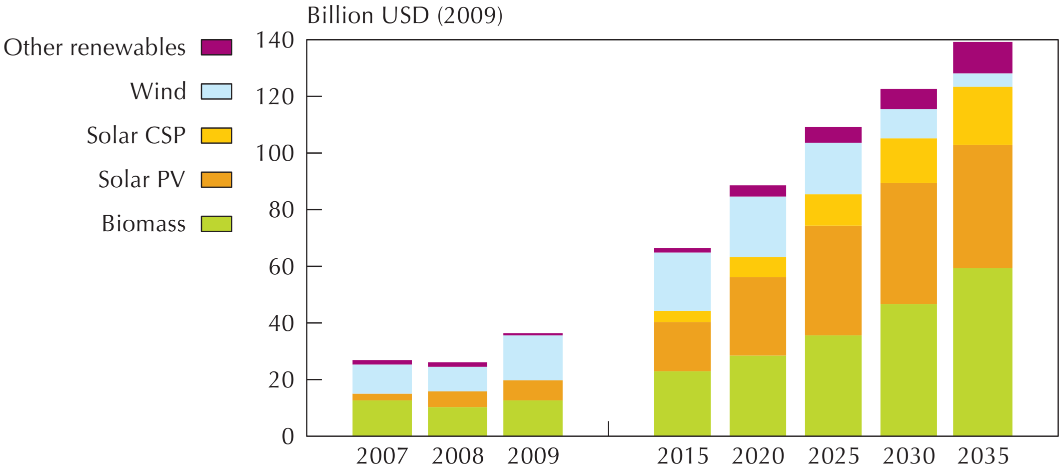
[1] The calculus first takes all PV as utility-scale, with a cheaper starting point but a smaller learning rate than residential PV. It takes an even investment cost of USD 3/W – the cost of utility-scale systems in the most mature market, Germany, under the assumption that other markets will join this level. Third, an average between the cost at the beginning of each "doubling" period and the cost at its end is taken for unit PV cost. Fourth, it assumes that USD 1/W is the break-even point, i.e. *figures the discounted cumulative value of the electricity that would need to be produced anyway. This latter assumption allows deducting the discounted market value of the electricity produced from the gross cost of PV investment the difference being the "true" cost of support policies.*

[2] Grid parity opens the door to "net metering", where electric meters work both ways as electricity is bought and sold by consumers/producers at the same price. It would then become an acceptable means to support solar electricity deployment provided it varies by time of use and differs at peak, mid-peak and off peak times.

distinguish perceptions from realities. The gap between the true cost of support (the subsidy part) and the amount of investment increases at each doubling. The cost of PV support will peak and then decrease. It disappears after the break-even point is reached. A similar reasoning would apply to solar thermal electricity.

Ignoring discount (interest) rates, the calculation does not depend on any particular agenda. Speeding or slowing the diffusion of PV does not modify the bill. Optimising the deployment agenda would require introducing discounting and selecting hypotheses on the likely evolution of market electricity prices, competing technologies and environmental benefits, which are beyond the scope of this chapter. Examples are found in *WEO 2010* with an assessment of the costs of support policies to 2035 in the New Policy Scenario for renewables-based electricity generation (Figure 10.1).

Figure 10.1 **Global support for renewables-based electricity generation in the New Policy Scenario**



Note: Other renewables include small hydro, geothermal and marine power.

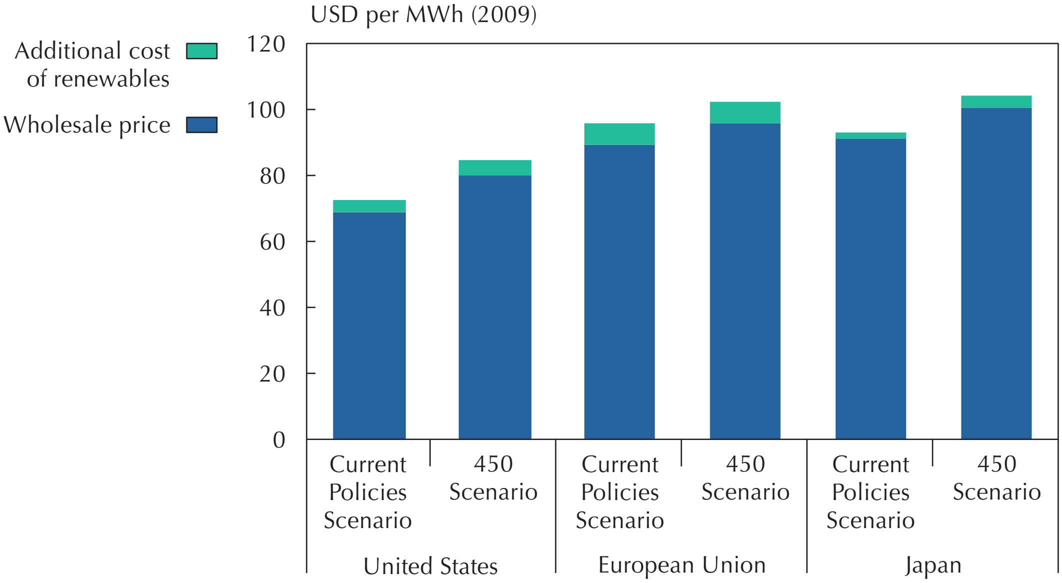
*Source: IEA, 2010*b.

Key point

Incentives for wind power diminish but incentives for solar electricity grow up to 2035.

WEO 2010 also provides a comparison between overall electricity prices, including CO_2 prices, and the impact of renewable support – calculated in the European Union, the United States and Japan. This greatly helps in putting the growing support costs in perspective. In 2009, support for renewable generation in the OECD+ countries ranged from USD 2/MWh to USD 8/MWh, equivalent to an average increase over and above the wholesale prices of 9%. Over the entire projection period, the average amount of the financial support for renewable generation per unit of total electricity produced (that is, electricity from both non-renewable and renewable sources) in the 450 Scenario is almost 30% higher than current levels. Despite the increase in the absolute level, the share over and above the wholesale price declines to just 6% on average in the OECD+ countries. In the European Union it is equivalent to 8% of the wholesale price, in the United States to 5% and in Japan to 3% (Figure 10.2).

Figure 10.2 **Average wholesale electricity (incl. CO_2) prices and impact of renewable support in selected OECD regions**



*Source: IEA, 2010*b.

Key point

Additional costs of renewables are limited compared to overall electricity costs.

Spend wisely, share widely

Funding to support solar energy deployment must be spent wisely, where the additional costs of solar electricity are null or lowest, and both efforts and benefits shared widely. The same support incentives will have greater leverage if they are spent in decentralised generation, peaking plants or hybridisation of existing (or unavoidable greenfield) fossil fuel plants – in sum, in projects that are less costly and/or have more expensive competitors, and above all in sunnier countries. As technology costs decline, leading profitable markets will increase in size and further reduce the level of subsidies implicit in support schemes.

To date, only Japan, Germany and a handful of European countries have been effectively deploying PV. The bulk of STE/CSP deployment has been concentrated in only two countries, Spain and the United States. This is changing as European countries are adjusting their incentives, many others are implementing new policies and some are setting targets for solar, particularly solar electricity: for example, 9GW PV and 1 GW CSP in China by 2015, 2 GW (PV & CSP) in Morocco, 20 GW (all solar technologies) in India, all by 2020, 1.2 GW (CSP) in South Africa, 7 GW (PV & CSP) in Egypt and Saudi Arabia, and 10 GW (7.2 GW CSP, 2.8 GW PV) in Algeria by 2030 – not counting additional capacities for exports.

Photo 10.1 **China only begins to use PV at home alongside solar thermal**

Source: Zheng Ruicheng, China Academy of Building Research.

Key point

At the end of 2011 China may emerge as world's third-largest PV market.

Effective support schemes today are based, directly or implicitly, on targets adopted by governments for shares of renewable energy. These targets may be either generic or detailed by resource, in their energy or electricity demand, at various time horizons. Even where support schemes are feed-in tariffs (FITs), targets are useful in setting expectations that developers, industries, bankers and investors may trust.

Setting ambitious targets also acts as an incentive for other governments to do the same – if not all economies can benefit from a prime-mover advantage, latecomers may suffer from a last-mover penalty.

This may also help both support and fine-tune each government's support policies. If it is possible to negotiate (perhaps in the framework of the United Nations Conference on Sustainable Development, the G20 or the Clean Energy Ministerial) some kind of international agreement to deploy solar energy technologies, a global, concerted strategy could emerge from the current patchwork of national initiatives.

The setting of targets and policies and their implementation are not only matters for national governments. Indeed, targets implemented at sub-national levels have often proven more ambitious than national objectives (IEA, 2009*d*). Sub-national authorities are playing a growing role in the deployment of renewable energies. The Spanish ordinances that make solar water heating mandatory in new multi-dwelling buildings were first adopted by the municipality of Barcelona, then several other cities and provinces, before becoming national policy.

Rio+20 *et al*, opportunities to accelerate the deployment of solar energy?

Negotiations to prepare for Rio+20 (or any of several other international for a, such as the G20 and the Clean Energy Ministerial) may offer an opportunity to negotiate and implement new policy schemes aiming at accelerating the speed of deployment of renewable energy technologies, on both climate change mitigation and development grounds, while also contributing to energy security/access and poverty eradication.

Countries may want to consider informal and non-binding objectives relative to the minimum share of solar energy in their final energy demand. These could be reached by any combination of technologies to satisfy any type of energy demand, in particular on- and off-grid electricity and heat for space and water heating, crop drying and cooking.

This approach may have greater chances of success than earlier attempts to negotiate broader renewable energy targets, because all countries are near zero with respect to directly using solar energy. A similar objective could be proposed to all countries of, say, 2% to 3% by 2020. If all renewables were to be taken into account, the considerable diversity of starting points and resources would require differentiating targets for each country. The success of a similar negotiation within the European Union should not mask the extreme difficulty of such an exercise among about 200 sovereign states. Furthermore, biomass and large hydropower could prove controversial.

The differences in solar resources are smaller than for most other renewable resources, but they exist. To make things easier to less-sunny but often more-windy countries, the objective could be based on solar and wind together. As wind is already profitable in so many places, the agreement would lose teeth and possibly be too easy for windy countries, compared to sunny ones. Conversely, a solar-only objective would be more demanding for less-sunny countries, but these – often the most industrialised ones – happen to have a larger potential for solar heat as they demand more space heating. They could also be allowed to meet their objective in helping others exceed their own aims through some sort of flexibility mechanism.

Such an agreement would complement but not substitute for a climate change mitigation agreement. It could prove easier to negotiate and implement, as it could more easily be perceived as an opportunity for development, not a restriction of any kind. It would be stable, offering little incentive for defection. It could help share the costs of making solar energy technologies competitive, and make them more attractive to investors in giving greater confidence in sustainable deployment. It would also help ensure the wide sharing of the benefits for the environment at all scales, for energy security and energy access, and for industrial development and employment.

In Morocco, several development banks are taking part in the financing of the first 125-MW CSP plant in Ouarzazate with conditional loans, thereby reducing costs of capital. They are the French AFD, the German KfW, the European Investment Bank (EIB), the African Development Bank, and the World Bank Group, notably with its Clean Technology Fund. Solar electricity is expected to satisfy 14% of the electricity demand of the Kingdom by 2020, or about 5% of its final energy demand.

Various suggestions have been made to establish global financing mechanisms to help developing economies deploy solar energy and adopt solar energy technologies, using global feed-in tariff funds. For example, the Global Energy Transfer Feed-in Tariffs for Developing Countries (GET-FIT Program) mechanism put forward by the DB Climate Change Advisors of the Deutsche Bank Group. GET-FIT would provide premium payments, passed through the national governments and utilities to independent power producers (IPPs). The utility would pay at least the market rate to the IPP, and there would be minimal additional burden on the electricity ratepayer. An international sponsor would provide an ultimate guarantee for the GET FIT payments. The climate change "money" pledged in Copenhagen by industrialised countries could take this path. For decentralised, off-grid installation, the scheme could involve a renewable energy service company, owned either by the local community or by third-party developers, in lieu of utilities.

Electricity trade can also be an important dimension of a global strategy to deploy solar energy. Umbrella export agreements, primarily from North Africa and Middle East to Europe, but also for example from Mexico to the United States or Australia to Indonesia, could help developers reach long-term power purchase agreements with prospective customers in those markets. This would help emerging projects achieve profitability and reach financial closure.

Support schemes

Most incentives to support the deployment of solar energy technologies to date have taken the form of feed-in tariffs (FITs) or feed-in premiums (FIPs). Both are long-term contracts offered to renewable energy producers based on electricity generation. FITs guarantee special rates for renewable electricity provided to the grid, while FIPs supplement the normal market prices.

FITs and FIPs have a demonstrated ability to jumpstart the deployment of solar electricity, whether photovoltaic or thermal, which other incentive schemes still need to prove on a similar scale. They can take the form of renewable energy portfolio standards (RPS), *i.e.* obligations imposed upon utilities to include a given share of renewable energy sources in their generating mix. RPS can lead utilities to propose long-term power purchase agreements (PPAs) to solar project developers. They can also lead to the creation of markets for renewable energy certificates (RECs). Tenders for competitive bids are increasingly being used, in particular in developing economies. And finally tax credits are also widely used, either in isolation or in conjunction with other support schemes.

Performances of support systems vary considerably from country to country. For the more mature technologies and markets, such as wind power, IEA analysis reveals three realities: very efficacious policies that are also cost-effective; policies that are efficacious but at a very high cost; and policies that fail to be efficacious even though incentive levels could be considered to be excessive (IEA, 2008*d*; IEA, 2011*h*). It shows no general superiority of one system over others. This underlines the importance of the non-market barriers that may stand in the way of effective deployment, and the need to design specific policy measures to overcome them.

RECs markets are usually considered better suited to more mature technologies than to emerging ones. Even for a mature technology like wind, however, several countries with RECs systems reportedly intend to move in the next few years towards FITs (UK) or tenders (Italy), to reduce system costs (but the Netherlands may go the other way, moving from FITs to RPS).

While FITs have been criticised as providing investors with weak stimulus to reduce costs due to very stable cash-flow perspectives, this may have finally turned into an advantage as reducing investors' risks allowed reducing the costs of capital. As up-front investments represent the bulk of the cost of renewables, the cost of capital to utilities or developers has a direct and important bearing on the levelised cost of electricity. Emerging technologies usually bear some technology risks; they can hardly bear large market risks at the same time, which in the case of solar electricity arise from the volatility of fossil fuel prices, as shown below. A secure framework reduces the costs of capital, and thus the cost of solar energy. For this reason, RPS work more effectively if they drive utilities to offer long-term, stable PPAs to solar project developers.

However, FITs do not by themselves offer policy makers easy control over the policy costs, a legitimate preoccupation. FITs or FIPs control the level of incentives but not the amount of investments made – as the regulator does not accurately know the rapidly changing technology costs. RPS control the investment, but not the incentive level, for the same reason. Tenders could in theory provide a solution to the dilemma but are less suitable for small-scale projects and do not necessarily deliver large projects when aggressive bidding drives remuneration levels too low.

Most systems in practice mix elements of price control and quantity control. For example, most RPS with solar set-asides also have solar-specific alternative compliance payments (SACP), setting an upper limit for the cost of RPS solar compliance. This also serves to cap prices for all RECs in the entire RPS. Another approach is the Spanish FIP for STE/CSP plants, which is only valid for a yearly total aggregate capacity (500 MW) of newly-built plants.

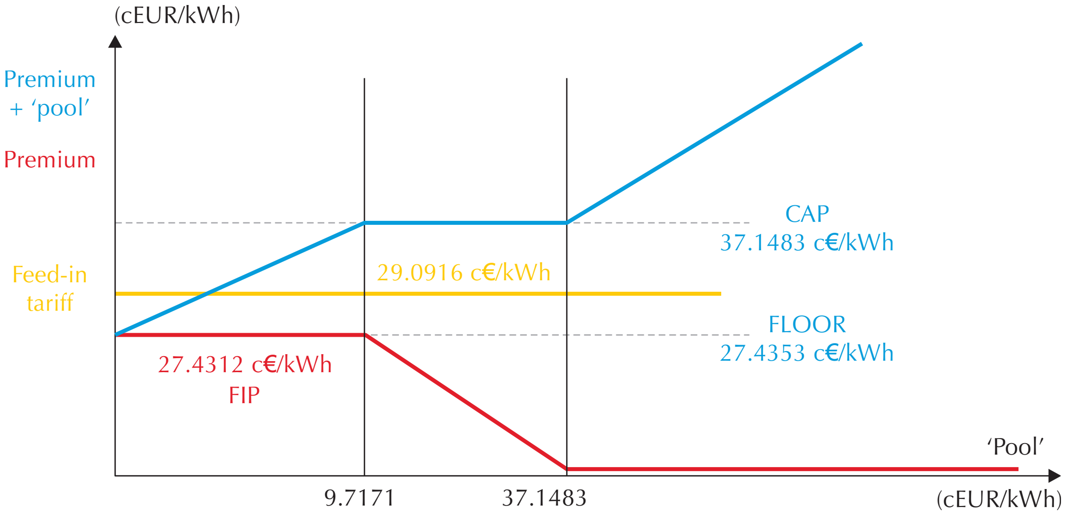
Feed-in tariffs and feed-in premiums

FITs or FIPs have demonstrated efficacy in the absence of strong non-economic barriers, but are not necessarily cost-effective. Further, even if cost-effective, they do not offer policy makers an easy control over total costs, *i.e.* they can prove "too effective" in driving investments beyond or faster than expectations.

Generous incentives, inconsistent with declining PV costs, have been and still are available in several countries. This might be necessary to jumpstart a new activity by providing potential investors with attractive returns. However, sustained high-level support is inconsistent with declining PV cost and encourages intermediaries to appear in the PV development business. FITs and FIPs are usually paid by electricity customers (ratepayers) and linked to their consumption, not through public spending (taxpayers), except in the Netherlands and Spain.

Over time, FIPs could possibly be preferred over FITs, as they expose renewable energy investors to greater competition as technologies and markets mature. In case of CSP, as with the optional FIP for CSP plants in Spain (Figure 10.3), increased exposure to competition would not only drive efficiency improvements, but more specifically drive plant operators to use their thermal storage capacities to better serve the needs of the economy and the grid by shifting electricity generation to times of highest value, *i.e.* peak demand (or net peak demand if the variability of wind and PV is considered).

Figure 10.3 **Spanish FIP for STE/CSP plants in 2011**



Notes: For CSP owners choosing the FIP, when spot prices (on the horizontal axis) are less than EUR 97.171/MWh, electricity from CSP plants receives a "premium of reference" of EUR 274.312/MWh. From this point to spot prices of EUR 371.483/MWh, the total remuneration is set at this level. Above this, only spot prices apply. Alternatively, a FIT of EUR 290.916/MWh applies.

Source: Montoya/IDEA.

Key point

For CSP plants, FIPs are more conducive to system-friendly operations.

Another reason to favour FIPs could be educational: laymen and vested-interest lobbies tend to equate FITs to pure subsidies, although they include a payment for the electricity. In fact, the true cost of FITs should be calcultated net of the cost of electricity that did not have to be generated by other means (in the case of wind today, the subsidy component is minor). FIPs appear to be smaller amounts than FITs, as they only supplement market payments made separately. They would thus presumably be more acceptable even though their benefit could be as great as a FIT.

On the other hand, the perception of FIPs as pure subsidies will be stronger than for FITs. Over time, however, this too may prove wrong. As large penetration of renewables reduces wholesale prices, as explained below, even FIPs will represent legitimate payments for solar electricity and not only subsidies, despite all appearances.

So far most of the rapid growth of PV has taken place in a very limited number of markets, all driven by FITs. Germany, Spain, Italy and the Czech Republic account for over 60% of global capacity (Figure 3.1). About half of global capacity is in Germany alone.

Generous incentives, inconsistent with declining PV costs, have been and still are available in several countries. This has encouraged intermediaries to appear in the PV development business, since projects allow for relatively high returns. Final investors harnessed reasonable returns, while intermediaries captured excessive rewards. While the market recognised how PV costs have been dropping sharply, regulation often did not follow a similar path. Potential market changes were not considered at the start and remuneration levels remained too high.

Difficulties began in Spain in 2008, when installed capacity reached 4 GW, almost 10 times more than the official target at that time. Since 2009 drastic future PV remuneration cuts have been enforced (-70% of 2008 tariffs), further reductions programmed, and what industry claims as retroactive regulation applied.[3] Also relatively high new targets are defined for 2020 (8.4 GW). These adjustments have undermined investors' confidence.

In Italy, PV accelerated in 2010, with 3.1 GW cumulative capacities in 2010 and 4 GW awaiting connection, according to GSE, the public renewables institution. If all this capacity is connected, 87% of the 2020 targets will be met already by 2011. The Czech Republic and France have experienced similar unexpected outcomes. Greece may be next, with one of the most generous FITs in Europe, very good sunshine, and more than 5.3 GW of applications for PV capacities towards a 2020 target of 2.2 GW. A target of 10 GW by 2025 was set in early September 2011, mostly for exports to Germany. Last but not least, in Germany, where some 8.5 GW were installed in 2010, the growth rate still exceeds that which would be consistent with the 2020 targets (about 3.6 GW/y).

The German FIT, after several revisions and adjustments, is probably the most sophisticated to date. In 2008 a "corridor system" was introduced that ties the rate of regression in support level to the recent rate of investments. Despite this, three non-scheduled decreases in support levels were introduced in 2010 and 2011. They have considerably helped keep the FIT levels – more precisely, the net present value of all future payments – quite close to actual PV costs in Germany (Figure 10.4), which due to market maturity are significantly lower than in sunnier countries. It remains to be seen, however, whether both scheduled and non-scheduled tariff decreases have provided German policy makers with the greater level of control on total costs passed on to electricity end-users they were seeking. The most recent information is encouraging, as PV systems commissioned between March and May 2011 in Germany were about 700 MW, likely to lead to a yearly increase of 2.8 GW, much closer to target than in 2010.

Cost control appears especially difficult in the case of PV. PV is extremely modular, easy and fast to install and accessible to the general public. 288 000 installations of less than 100 kWp were installed in Germany over 12 months (Figure 10.5) – almost three times the cumulative

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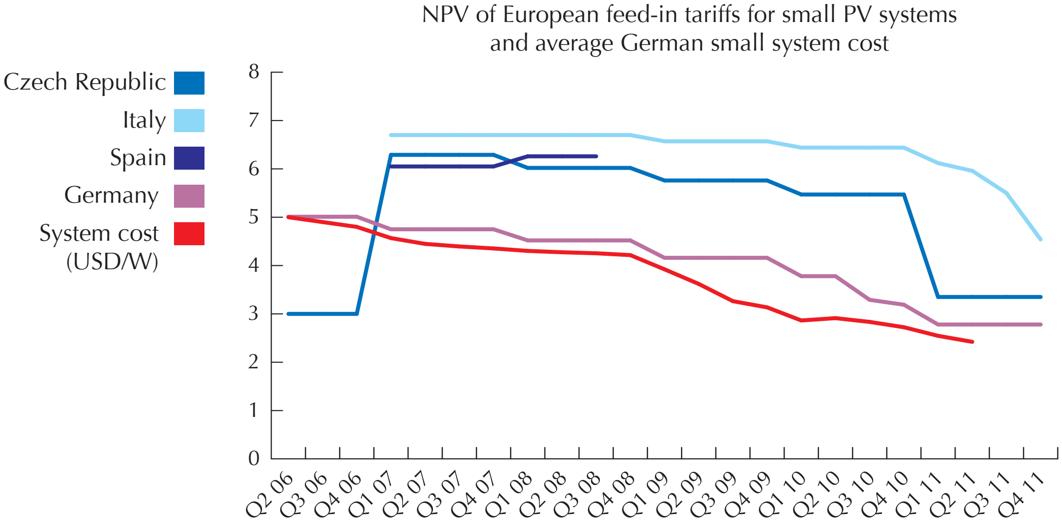
[3] *The number of full-capacity hours at which the tariff is paid was limited. Investors having PV systems that are oversized in relation to their rated and contractual capacities are likely to be hardest hit.*

ambition of the initial programme. They totalled 62% of the added capacity, the remainder being provided by less than 1 200 larger installations.

As a result, the supply curve seems rather flat, reflecting considerable potential at a given cost. Controlling quantities would require a very precise price setting in an uncertain and ever-changing economic environment. At any time, the incentive level risks being either "too high", not generating too-high returns to investors but driving more PV investments in PV than wished, or "too low" and much less investment than desired will take place. The difficulty is illustrated in Figure 10.6.

Figure 10.4 **Net present value of European FITs for PV and PV system costs (USD/W)**



Notes: As of Q2 2011, with expected tariffs for the remainder of the year. NPV calculated at 4% discount rate; system cost represents German average and excludes impacts of value-based pricing in high FIT markets.

Source: Bloomberg New Energy Finance.

Key point

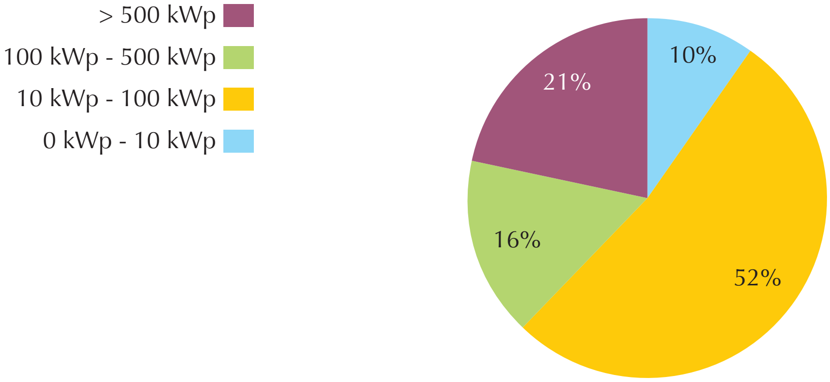
Frequent revisions have allowed the German FIT for PV to avoid overpayments.

One possible transitory answer to concerns about rapidly increasing costs of PV support policies could be to "cap" the quantities – per year, per quarter, or per month – of new capacities allowed to benefit from the FITs. Another option would be to cap the level of annual finance commitments to the FITs. These approaches would provide policy makers with direct control over the money fluxes, while linking any decrease in tariff level with an increase in allowed capacities.

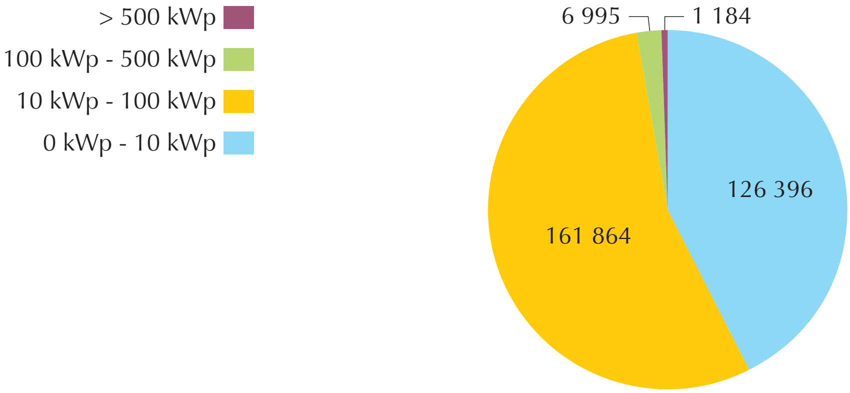
The PV industry tends to oppose both options, particularly on the grounds that they risk choking off the dynamics of PV installations. They would make any PV development uncertain, as each would depend on its place in a queue and how the queue is handled – not an easy task for regulators either. One may wonder if regular, unscheduled tariff changes are much better. Leaving policy makers with the option of decreasing support levels entails the risk that these levels are inadvertently set too low and the braking ends up being much stronger than desirable. Perhaps more importantly, unscheduled changes could cause investors to lose faith entirely in the programme and render it ineffective in the future.

Figure 10.5 **New PV installations in Germany, from October 2009 to October 2010**

Share of installed capacity by size of installation



Number of installations by size of installation



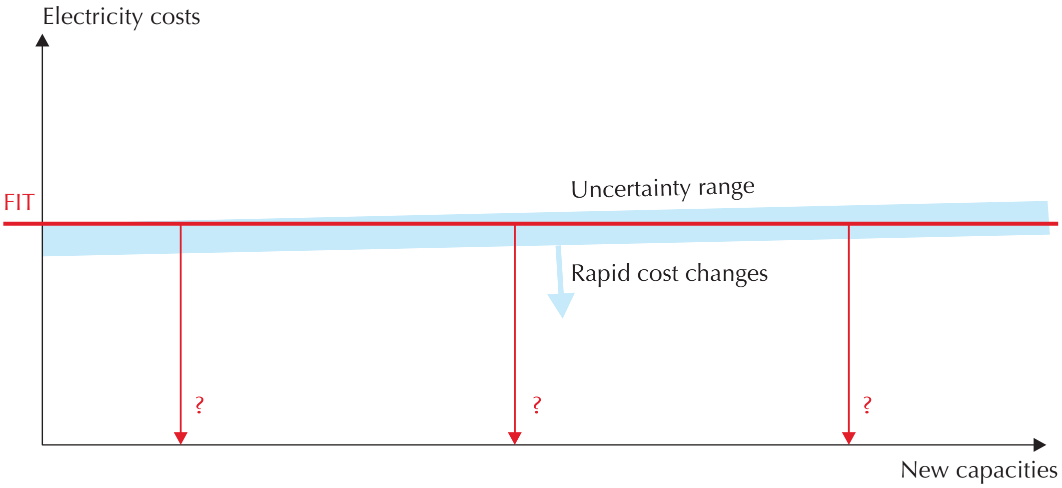
Source: Bundesnetzagentur.

Key point

PV growth in Germany is driven by thousands of small, local initiatives.

Whatever option is chosen, policy makers and stakeholders alike have a real interest in making their short- and mid-term objectives explicit in quantitative terms. This might help reconcile the somewhat conflicting recommendations of adjusting support levels frequently enough to keep pace with rapid cost reductions and avoid over-paying, while providing investors with a stable, predictable policy environment.

Figure 10.6 **Schematic illustration of the difficulty in controlling overall costs in setting FIT levels**



Notes: The red line represents the FIT level. The blue line represents the uncertain, "flat" and fast-moving (as symbolised by the arrow) PV supply curve. The FIT may deliver much more or much less than expected, as the three vertical red lines suggest.

Key point

Frequently adjusted FIT levels control marginal costs, but not necessarily total costs.

Greater international co-ordination may also help smooth out variations. PV bubbles and bursts have been created when investors left some countries for others because of different policy decisions, tariff level differentials, and other framework conditions. In Europe, this made the task of German policy makers difficult as the German market seemed to be the market of last resort. When very profitable options are no longer available in other countries, the PV industry prefers the low returns of the German market to keeping modules in their stocks. If other governments take strong limitative decisions (whether through price or quantity controls), Germany will again run the risk of rather uncontrolled PV market growth. Enhancing collaboration among countries to expand markets and reduce price differentials – taking into account the different solar resources and market maturity levels – appears to be an important policy priority from this perspective as well.

Beyond increased coordination at a regional level, the implementation of support policies in a larger number of countries, or an increase in the ambition level of existing objectives and policies in various countries, could also help smooth out the deployment of solar electricity and alleviate the concerns over overall policy costs that uncapped FITs in too few countries have been raising.

Renewable energy portfolio standards and solar renewable energy certificates

Under RPS, utilities are encouraged to secure generation from renewables by offering renewable generating capacity long-term, stable PPAs. Solar RECs (SRECs) allow distinguishing the electricity itself from its green nature or guaranteed origin (the sun). Both can be subject to bilateral, long-term contracts or be sold on the spot markets. To fulfil its RPS obligations, an investor in PV can sell the electricity to the company that serves its community and also sell the RECs directly or indirectly to another in greater need.

In the United States, out of 30 states having an RPS, at least 16 now have solar set-asides (or carve-outs) or solar RECs (SRECs), *i.e.* specific targets given to utilities relative to solar energy sources. Given the current technology costs, solar technologies benefit from RPS and certified emission reduction (CER) systems only if these are completed with some form of "technology-banding" or "resource-banding" such as SRECs. Another form of banding is to give solar kWh a multiplier when it is counted towards the RPS obligations, thus multiplying the market value of associated RECs.

There is one important exception: California. It has a combination of an ambitious RPS (33% of renewable electricity by 2020) with no solar set-aside. This approach is possible because the state has good sunshine, a good match between sunshine and demand peaks reflected in time of use electricity pricing, and other forms of support such as the federal Business Energy Investment Tax Credit (ITC) and the Department of Energy's loan guarantees. Together these are expected to drive very significant solar deployment in the next few years – mostly CSP and utility-scale PV plants. California also has a set of initiatives and programmes, including FITs, which provide incentives to customers to install in particular distributed PV systems, indirectly contributing to RPS by reducing demand on utilities.

Solar ambitions in RPS have been limited so far, except in New Jersey, the second-largest PV market in the United States next to California, and possibly the only one that actually develops on the basis of tradable RECs. Such schemes are progressively increasing, and so will solar electricity investments in the United States. Some other countries have a general preference for RPS and RECs, but not all have SRECs or solar multipliers, which means that they have very little development of solar electricity. Of the six Member States of the European Union that currently base the deployment of renewables in the power sector on REC systems, three – Belgium, Italy and UK – also have FITs for small-scale projects that benefit residential and commercial PV systems. Some RPS allow solar water heaters at customers' locations to be counted towards the RPS of utilities (*e.g.*, in Australia and four US States).

To be effective, RPS must not offer utilities a too easy or too low-cost way out with low price caps (*i.e.* the possibility of not complying with the RPS against a payment or fee). One interesting option to strengthen RPS is to link any authorisation to build new fossil-fuel plants with the achievement of renewable capacities. If for example a country aims to achieve 5% solar electricity generation in ten years while its overall electricity generation is expected to increase by 10%, the government could require that all utilities build or contract for 1 TWh of solar for each additional TWh of conventional power.

Requests for tenders

Requests for tenders are formal invitations to suppliers to bid for the opportunity to supply products or services. Tenders are increasingly chosen in both industrialised and developing economies as preferred support instruments for early deployment of renewable electricity. They offer full control on the overall capacities, and allow for price discovery through competitive bidding – provided competition exists. However, tenders entail transaction costs and can hardly be adapted to small-scale projects unless project aggregators step in. Apart from the risks of bribery or nepotism where the rule of law is weak, tenders run the risk that very aggressive bidding by inexperienced – or gaming – developers might fail to deliver the capacity, precisely because contracted prices end up lower than actual costs. (This is called the winner's curse dilemma in auction theory.) The deployment of wind in Brazil, which moved from a FIT to tender, offers a case in point. The average tariffs under the tender concluded in 2010 were only half the tariffs of the earlier FIT, but at least a quarter of the 3.1 GW wind capacity tendered is considered at risk by Bloomberg New Energy Finance's analysts for providing too low return on equity. Only a fifth had already reached financial closure in the first half of 2011.

Another risk relative to not-yet mature technologies is that competitive pressures lead developers to use lower cost, lower quality assets, which may then underperform and be unable to cover their debt. Immature technologies may also witness the opposite risk, *i.e.* lack of competition if too few experienced actors can take part. These risks can be alleviated by specific measures but suggest that requests for tenders should be used with care, and are more easily designed for mature markets and technologies than for emerging ones.

Tax credits

A wide variety of tax credits are or have been used in many countries to support the deployment of solar energy. While production tax credits (PTC) are, like other support schemes, linked to the actual production of renewable energy, investment tax credits (ITC) directly support investments. ITCs run the risk of supporting low-productivity investments, as has been seen in the past with wind power in some countries. This risk, however, is minimal if ITC level is adjusted so that the actual energy output is necessary to make these investments profitable, whether through another support mechanism or through its market value. ITCs are more effective in directly addressing the high up-front costs and technology risks associated with the early deployment of expensive nascent technologies.

ITC can support a broad set of technologies with relatively low transaction costs, as no measure of the actual output is required. In the United States the federal business energy ITC supports solar water heat, solar space heat, solar thermal electric, solar thermal process heat, photovoltaics, and even solar hybrid lighting. The credit is equal to 30% of expenditures for solar energy equipment, and is in place up to 2016. The American Recovery and Reinvestment Act of 2009 further allows eligible taxpayers to receive a grant from the US Treasury Department instead of taking the ITC (or the renewable energy PTC) for systems for which construction begins before the end of 2011.

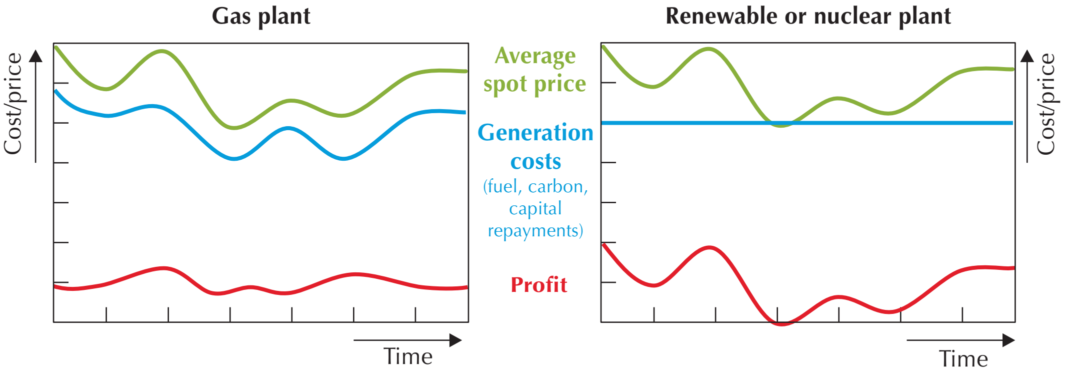
Market design

The greatest uncertainty affecting the emergence of profitable solar electricity rests with fluctuating fossil fuel prices. In fact, fossil fuel price volatility is a bigger problem for renewable energy project developers than for fossil fuels. This results from the design of standard wholesale electricity markets, in which marginal pricing determines the spot-market price of electricity. Generators offer capacity into the market at a price sufficient to recover their short-term running costs (including fuel and carbon costs). Capacity is dispatched starting with the lowest-price offer, moving up to more expensive options until demand is met. Under normal conditions, the offer price of the last unit of generation dispatched (the "marginal" unit of generation) sets the market price for electricity, which is paid for all generation dispatched irrespective of their individual offers (giving birth to what is called "infra-marginal rents").

Perhaps counter-intuitively, nuclear and renewable generators can be more exposed to fuel and carbon price uncertainty than fossil-fuel generators under marginal pricing. A gas-fired combined-cycle plant that sets the marginal price will generally recover its operating costs (including fuel and carbon), because the electricity price adjusts to cover these costs. It will also benefit from higher prices during peak periods to recover its modest capital costs. Ultimately, the gas-fired generators' profits are not strongly exposed to fluctuations in the price of gas or carbon, as long as the generation is setting the marginal price.

Conversely, the profitability of a plant that has high capital investment costs but very low short-term running costs (such as a nuclear or renewables) is strongly exposed to uncertainty in gas or carbon prices, as these set the market price of electricity, and hence determine the revenue available to cover these plants' high capital costs (Figure 10.7).

Figure 10.7 **Schematic of profit variability from electricity generation**



Source: IEA, 2011f.

Key point

Fuel cost variability is a bigger concern for non-fossil renewables generators.

This raises the question of whether current electricity market designs make investment in low-carbon technologies, which typically have high up-front capital costs, riskier than continued investment in fossil-fuel plants. This elevated risk could deter investment in low-carbon generation, even where carbon pricing or other policy interventions have made it cost-effective. At present, long-term fixed payments, whether from FITs or RPS-driven PPAs, are required to shield project developers from this profit uncertainty. To a lesser extent, FIPs and RECs markets also reduce the economic risks.

Current market designs based on marginal pricing also have important effects when large shares of renewable electricity are introduced. There are increasingly times during which fossil-fuel plants are not needed to meet demand, so these plants no longer set the electricity price. The market price at such times drop to the much lower costs of renewable generators, as has already being seen in the German and Spanish electricity markets with large penetration of wind power. One immediate effect is that wholesale electricity prices are reduced, to the benefit of deregulated customers. Unfortunately, this effect – one of several so-called "merit-order effects" – is hardly noticeable on customer bills. It is hidden by other cost variation factors, while an "add-on" to the price of electricity is usually made very explicit and understood as a pure subsidy for renewables, which it is only in (declining) part. Longer-term effects are considered below.

In deregulated markets, a large share of renewables very often leads to low wholesale electricity spot prices. While higher peak prices (and associated infra-marginal rents) could theoretically compensate, this would be a highly uncertain and volatile revenue stream, making investments for new generating capacities riskier and more difficult to finance. This could affect both additional renewable capacities, and fossil-fuelled plants required to serve as balancing plants. Solar electricity generating capacities, even offering competitive prices, may not develop further in electricity spot markets based on marginal pricing, *i.e.* driven by marginal running costs. Offers are confronted every minute, while investors in solar capacities require visibility of income for 15 or 20 years.

The conventional wisdom is that when renewables reach competitiveness, support systems must be dismantled. While support schemes should certainly not convey a permanent "subsidy", it is yet unclear how electricity markets should be designed to support continuous deployment of renewables. This question is relevant not only for the long term, when shares of renewables in electricity generation are expected to reach very high levels, but already today for wind, and in the next few years for solar energy in the many competitive situations that are emerging.

Several governments have begun to publish proposals to address this factor. The UK government, which foresees low capacity margins in its electric system by 2018, proposed in December 2010 to introduce a capacity mechanism to contract for avoiding shortages. This would involve payments to generators for maintaining contracted amounts of surplus availability to supply the market. Such an approach is more likely to keep fossil-fuelled plants in operation even with unprofitably low capacity factors, rather than to extend the development of renewable capacities.

The current UK proposal for renewable electricity, called "contracts for difference FIT", looks like an adjustable FIP similar in principle to the FIP for CSP in Spain. This is a proven solution for the short term but leaves open the longer-term issues.

Effective, long-term market design for renewable electricity markets is yet to be conceived. As solar energy technologies come closer to becoming competitive, it is important that governments do not prematurely dismantle effective and cost-effective incentive schemes before they set up equally effective and cost-effective electricity markets, able to reward continuous investments in new renewable capacities and enabling technologies (grid upgrades, demand-side management, interconnections, storage and balancing capacities).

Very large penetration of renewables[4] will affect not only electricity markets, but more broadly energy markets, in ways that make achieving competitiveness look like a mirage. In getting closer to the big picture described in the next chapter, renewables (led by solar and wind energy technologies) will progressively take the lion's share in the energy system as a whole. The penetration of renewable electricity will progressively, even if partially, displace fossil fuels (whether coal, oil or gas) in most uses, thereby slowing the growth of global demand for fossil fuels and, ceteris paribus, of their prices.

The remarks made above relative to electricity prices can be broadened to energy markets. The deployment of solar technologies will not only reduce their own costs and prices through learning; they may also reduce the prices of their largest competitors, fossil fuels. Deploying renewables on the very large scale (that only solar and wind can deliver) might be, despite current appearances, an effective way to keep overall energy prices affordable in the long run. Somewhat paradoxically, long-term price increases may be limited by including technologies that are still among the costliest today in our overall energy portfolio. Equally paradoxical, a massive deployment of renewables could make it more difficult for them to achieve competitive cost levels. This is where CO_2 pricing could help.

CO_2 pricing

CO_2 pricing has played a modest role in the development of solar energy technologies so far. The Global Environment Facility under the UNFCCC has supported integrated solar combined cycle plants in developing countries. This played a bridging role in maintaining competences between the first generation of plants in the 1980s and the second in the 2000s. But the funding came from governments' money, not CO_2 pricing. A few solar projects have benefited from the Clean Development Mechanism, but Certified Emission Reductions (CERs) seem to have provided only a marginal incentive. Emission trading schemes or carbon taxes, in countries employing such schemes, have similarly played a marginal role in making solar energy projects profitable.

Some economists argue that the overlapping of CO_2 pricing and renewables policy instruments increases the costs of achieving the climate mitigation objectives. Climate policies should be technology-neutral, for governments are not good at picking winners, they say. This argument overlooks learning and considers cost-effectiveness only in the short run. Long-run cost-effectiveness considerations lead to different conclusions and fully legitimise specific support incentive schemes for nascent technologies with large room for cost decrease through learning (IEA, 2011*f*). This could apply to solar energy technologies, even if CO_2 emissions are priced one way or another. Ultimately, as Azar and Sandén (2011) argue, the debate should not be about "whether" climate policies should be technology specific, but "how" technology-specific the policies should be.

For example, it makes sense to differentiate levels of incentives for building-integrated PV and for simpler building-adapted PV or commercial PV, in order to foster solutions that make PV an integrated part of building envelopes and not simple add-ons.

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[4] Indeed they already provide benefits in mitigating fossil fuel price volatility, as shown by the application of the portfolio theory (Awerbuch and Berger, 2003).

It would make less sense to favour one module technology over another. Similarly, for utility-scale solar plants, it may not be advisable to differentiate tariff levels between PV and CSP, even less so between different types of PV or different types of CSP. Apart from some global support, markets should be encouraged to choose the technologies that best fit their needs – by, for example, rewarding thermal storage of CSP plants through time-of-use pricing, or possibly distinguishing different availability factors through specific payments. Hybridisation with fossil fuels should not be discouraged by arbitrarily limiting the share of fossil *versus* solar energy inputs, but solar incentives should be made available only to electricity generated from solar energy.

In the longer run, CO_2 pricing could become the most efficient way to introduce a wedge between fossil fuel costs and prices. In some scenarios, it may stop fuel prices from collapsing, thereby preserving the competitiveness of renewables. CO_2 pricing would thus support not only solar and other renewable energy technologies, but also energy efficiency improvements, including those related to penetration of efficient electricity technologies in many energy uses; such technologies are enabling solar and other renewables to increase their shares in the broader energy mix.

Paving the way

Most solar electricity capacities today have resulted from the implementation of FITs. FITs should therefore be considered the primary option for jumpstarting new solar electricity markets, especially if small-scale PV is likely to represent the bulk of investments. Some generosity in incentive levels might be the price to pay for the initial take-off.

However, after some time as markets grow, cost concerns gain greater attention from policy makers; incentive levels need to be more precisely calibrated and possibly quantitative limits considered. As technologies and markets further mature, and especially for large-scale systems, other, more market-oriented support schemes might be preferred, whether FIPs, RPSs or tenders, possibly associated with tax credits. Innovation could receive specific support, such as the loan guarantees developed by the US Department of Energy and expanded by the Recovery Act of 2009.

In the longer term, if solar energy – and especially solar electricity, as suggested in the next chapter – is to reach very high penetration levels, electricity markets will need to undergo some deep changes. Current design is unlikely to attract enough investment into solar electric capacities, other renewables or the enabling technology environment – whether balancing plants, storage capacities, smart grids or super grids. Pricing the environmental harms of each particular form of energy generation, starting with climate change from CO_2 emissions, should naturally be part of these market design changes.

While incentive schemes for early deployment today represent the greatest challenge for the development of solar electricity, there are other important policy issues. For example, ensuring sufficient investment in research and development (R&D) is the main challenge confronting solar fuels, and still an issue for all other solar energy technologies. Solar heat is too often ignored by policy makers, and by architects and engineers. Its deployment is mostly impeded by non-economic barriers and split incentives such as differing landlord-tenant priorities. Financing is the main barrier to large-scale dissemination of off-grid systems (see Box: Financing off-grid solar electrification), and remains a very important dimension for all solar technologies, which have high up-front investment costs but low running costs.

Policy makers need to address all these issues. Apart from the policy considerations in earlier chapters of this publication, various aspects were also considered in the IEA Technology Roadmaps on solar PV and CSP (IEA, 2010*c*; IEA, 2010*d*), and more will be looked at in the forthcoming IEA Technology Roadmap for solar heating and cooling.

Financing off-grid solar electrification

Small-scale solar electricity systems, most often PV, can bring considerable benefit to "base of the pyramid" consumers, *i.e.* the poor in poor countries. These people earn very small amounts of money on an irregular basis, and spend significant shares of it on dry batteries, kerosene and other energy products. According to some estimates, in rural areas those earning USD 1.25 per day may spend as much as USD 0.40 per day for energy.

Solar electricity is actually competitive, but up-front costs, ranging from USD 30 for pico PV systems to USD 75 000 for village mini-grids are usually too high. The financing dimension of solar energy deployment is perhaps most acute in this case.

Access to finance to support the high up-front investment costs of solar systems for rural electrification is scarce. Transactions costs are very high due to the disaggregated nature of the projects. The risks for potential third-party investors are high, especially given that financial institutions have little experience on rural electrification projects, and are not compensated by high rates of return. The main risks are:

- commercial risks: overall uncertainty, very low experience and lack of specific information on the present state of the market make it hard to plan and deal with the future;
- customer behaviour: fraud, default on the payment of bills;
- operating risks: credit risk (default or protracted default on payment from end-user);
- economic risks: inflation risk (affecting end-user's ability to pay), exchange rate risk (affecting the distributor's ability to correctly bill the end-user); and
- political risks: lack of political stability will affect the long-term assessment of policies to support rural electrification projects and the trustworthiness of investment contracts with states that might default on payments.

The key issue is for public authorities to develop and promote a clear political support scheme to leverage the private sector and allow the development of a safe business environment for the dissemination of solar systems and mini-grid installations. Once the risk is alleviated, equity funds and debt financers from commercial banks and private funds can be tapped in decentralised rural electrification projects.

Two distinct business models can then be put in place, the retail model and the energy service model.

In the **retail model**, best adapted to pico PV or solar home systems, the end-user buys the solar system from a private company. The cash or credit payment gives the buyer full ownership of the system. Public funds, multilateral or bilateral aid and the private banking sector can offer loans to support the banking institutions or the entity in charge of rural electrification. Supporting the purchase of the equipment by the private retailer and the end user is essential, as is expanding the network of retailers so they can supply the energy poor with affordable solar systems.

Helping end-users break down their payments into low monthly instalments is of paramount importance. In some countries, a large network of micro-financial institutions is present and established (Bangladesh and Grameen Shakti, Kenya and the Kenyan Women Finance Trust). These financiers can act as an efficient intermediary between governments, retailers and international institutions to promote and disseminate solar systems. They know the credit-worthiness of their clients and can offer efficient end-user finance solutions through micro-credit loans (even if the interest rates are high, the default on payments is usually very low). In Bangladesh, Grameen Shakti was successful in offering micro loans to distribute more than 500 000 solar home systems up to 2010.

In the **energy as a service** model, best adapted to mini-grids, the company provides the equipment to the end-user who will be paying for the service rendered. The ownership of the system remains in the hands of the company. The private operating company will need capital to buy the necessary equipment. It can either buy it using loans from the public or the private sector or attract equity investors. To support this intermediary, multilateral and bilateral aid using concessional soft loans and grants from donor funds can help decrease the high-front investment of the private operating company and reduce the burden on the end client. If a fee is to be paid by the client, micro-financial institutions can help spread the first payment.

Policy support could take the form of grants to lower the price of systems to end-users in the retail model. In the service model, it could take the form of subsidies to company or to end user to reduce the price of electricity and insure a minimum return on investment to the investor.

Chapter 11
Testing the limits

Solar energy technologies for electricity, heat and fuels have the potential to make solar energy the primary source of electricity, and an important contributor to our energy and transport needs. Solar energy could become the backbone of a largely renewable energy system worldwide in 50 years from now.

Rationale and caveat

This chapter explores whether and, if so, how the role of solar energy technologies can be much more important than envisioned in Chapters 3 to 5, which took into account data and factors consistent with our Technology Roadmaps and IEA modelling exercises. The purpose is to assess how far – and how fast – an integrated approach, building on synergies among various solar energy technologies, and among solar and other renewable and energy efficient technologies, could go.

Renewables in general, and solar energy in particular, may not always offer the lowest cost options to meet our energy needs, nor even the cheapest way of doing so while reducing global carbon emissions. But it is in the interest of policy makers and all stakeholders (including the general public) to understand what is possible and roughly affordable under three hypothetical conditions: if policy makers were to decide to reduce our reliance on fossil fuels, whether for security, economic or environmental reasons, more sharply than even in the IEA's most climate-friendly scenarios; or if many countries decided to abandon nuclear power; or if carbon capture and storage was found to be costlier, more limited or not as safe as hoped.

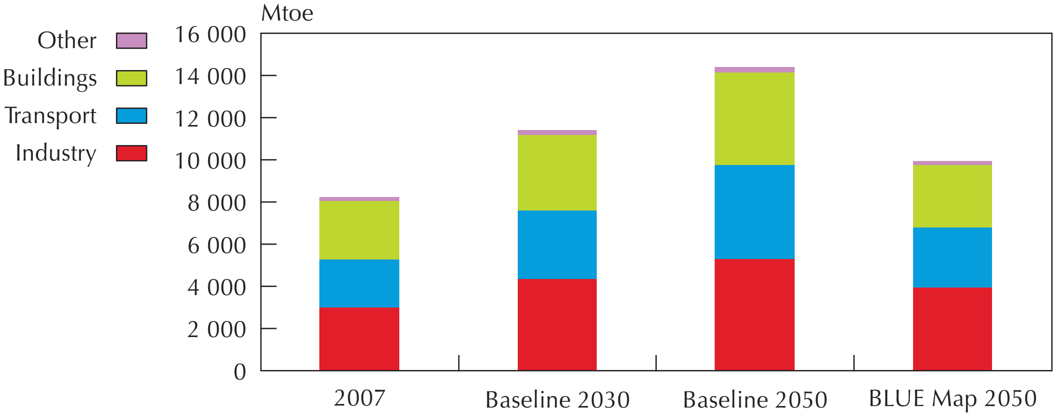
A portfolio approach is needed to decarbonise energy systems, and there are many uncertainties about all the conceivable options. For example, the UK Committee on Climate Change (2011) observes: "CCS technology is promising but highly uncertain, and will remain so until this technology is demonstrated at scale later in the decade. In the longer term, storage capacity may be a constraint." Furthermore, it notes that in the UK after Fukushima, "a full review is required to ensure that any safety lessons are learnt and to restore public confidence in the safety of nuclear power. Should the review suggest limiting the role of nuclear generation in the UK in future, then a higher renewables contribution would be required. Alternatively if the review leads to a significant tightening of safety regulations, nuclear costs may be increased, which would improve the relative economics of renewable technologies and argue for potentially increasing their role."

In sum, the risk that other options may fall short should motivate policy makers to consider possibilities for markedly higher penetration levels of renewables. These technologies utilise indigenous, inexhaustible resources and are by their very nature more secure than competitors. They are also less likely to experience price volatility, once the technologies are mature, are environmentally sustainable and the cheapest known antidote to catastrophic climate change, even if they are or appear to be higher-cost options in other ways.

The world in 50 years

The "big picture" considered in this chapter could be reality some 50 years or more from now. This future world has about 9 billion inhabitants, *versus* 7 billion today. Two billion live in cold or temperate countries or regions, seven billion live in hot and sunny countries. The world gross product increases fourfold but energy intensity has been considerably reduced, so the final energy demand is only 40% higher than in 2009. At 12 000 Mtoe or about 140 000 TWh, this final energy demand is foreseen as early as 2035 under current policies (*WEO 2010*). These figures are consistent with the assumption of the BLUE Map Scenario of *ETP 2010* for 2050 (Figure 11.1).

Figure 11.1 **Final energy use by sector in 2007, 2030 and 2050**



Note: 10 000 million tonnes oil equivalent (Mtoe) are equal to 116 000 TWh, or 0.418 Ej.

Source: IEA, 2010a.

Key point

Efficiency improvements can limit the growth of energy demand.

Energy efficiency improvements will result from technical progress and sound policies. A key driver of this reduced energy intensity will be the refurbishment of most current buildings, reducing the demand for space heating in OECD countries, economies in transition and China. Substitution of fossil fuels by electricity with heat pumps in commercial and residential sectors will also play a key role, as will electric traction in transportation. In industry, heat pumps and other efficient electric processes will also substitute for large amounts of fossil fuels, supported by an evolution of industry activities towards greater recycling. Heat pumps reduce energy consumption by a factor of four. Most population growth and construction of new buildings for all purposes will take place in sunny and warm countries, with cooling loads rather than heating needs. In the transport sector, electrification will reduce the effective energy demand, as one kWh of electricity in electric vehicles and plug-in hybrids replaces about 3 kWh of liquid fuels.

Each additional electric kWh increases the share of electricity in the final energy demand by, acting on both numerator and denominator. Hence the assumption relative to the limited growth of energy demand is inseparable from the assumption of a large substitution of electricity for direct uses of fossil fuels. One can thus assume that the share of electricity in the final energy demand would increase from slightly less than one fifth currently to at least half, perhaps even two-thirds, by 2060-65. These shares would represent yearly amounts of electricity of 70 000 TWh and 93 333 TWh, respectively. A rounded figure of 90 000 kWh would result from a multiplication by a factor of 4.5 of current electricity generation of about 20 000 kWh in 2008 and 2009 – in 50 years. This represents an annual growth rate of electricity consumption of 3%, still lower than the growth rate seen in the last 30 years. This assumption is thus not extreme: it does not ignore energy savings in the use of electricity, but combines them with displacement of fossil fuels by renewable electricity.

The necessary energy supply and use will be analysed first for electricity, then for non-electric uses of energy resources, whether fossil or renewables.

Electricity

Solar electricity could provide half of the projected electricity demand of 90 000 TWh, that is, 45 000 TWh, which could be broken down as follows: 18 000 TWh from solar PV, 25 000 TWh from CSP and 2 000 TWh from solar fuels (in this case, hydrogen). Required PV and CSP peak capacities would be 12 000 GW and 6 000 GW, respectively.

Three problems immediately come to mind: the costs, the variability of the resource, and the land requirements or “footprint”.

Costs

If appropriate deployment policies are conducted, the costs of solar electricity are expected to come down to a range of USD 50/MWh to USD 150/MWh by 2030 (chapters 3, 6 and 8). The low end is reached with utility-scale power plants in sunny countries, whether with PV or base load CSP generation; the upper end is characteristic of small-scale systems in less sunny areas such as central European countries. Most other energy sources by 2030, however, will present a roughly similar range of costs – all around USD 100/MWh, or USD 0.10/kWh, plus or minus 30%. On-shore wind is already 30% below, offshore currently 30% above. Fossil-fuel electricity generation from new plants would face either CO_2 pricing or the need to access more expensive resources if demand were not mitigated by energy efficiency and the deployment of renewables. New coal plants face tougher regulations on pollutants, nuclear power will face new safety requirements. Both have long lead times. The most likely competitors for solar electricity in the long run will be hydropower, electricity from biomass, and wind power.

If as projected the world is four times richer in 2060, but consuming only 50% more energy, even if the cost of one energy unit were twice as much as today, the total energy expenditure would be proportionally smaller than today. It is thus conceivable to prefer an energy future that provides security, economic stability and preserves the sustainability of ecosystems and the environment, even if it is not the least-cost option when such considerations are ignored.

It is important, however, to keep some sense of technical and economic realism. Options that can be brought to competitive markets in a decade, perhaps two decades, could be deployed thereafter on a massive scale, and play a large role by 2060. Options that are currently orders of magnitude too costly (*e.g.* 10 or 100 times costlier) may or may not be affordable in 20 years. So reasonable possibilities must be distinguished from the more speculative options (see box: ruled-out options). Significant cost differences will remain between sunny and less sunny countries. Cost considerations, combined with issues relating to variability, will limit the role of solar electricity in cold and temperate countries where other options, notably wind power and hydropower, are less costly and more convenient.

Ruled-out options

The following options are not considered in this chapter as they rest on very hypothetical grounds and/or would have costs several orders of magnitude higher than alternatives:

1. *Space-based solar power*

American scientist and aerospace engineer Peter Glaser imagined in 1968 space-based solar PV power plants using wireless power transmission to send energy to the earth, thus taking advantage of continuous and stronger sunshine.

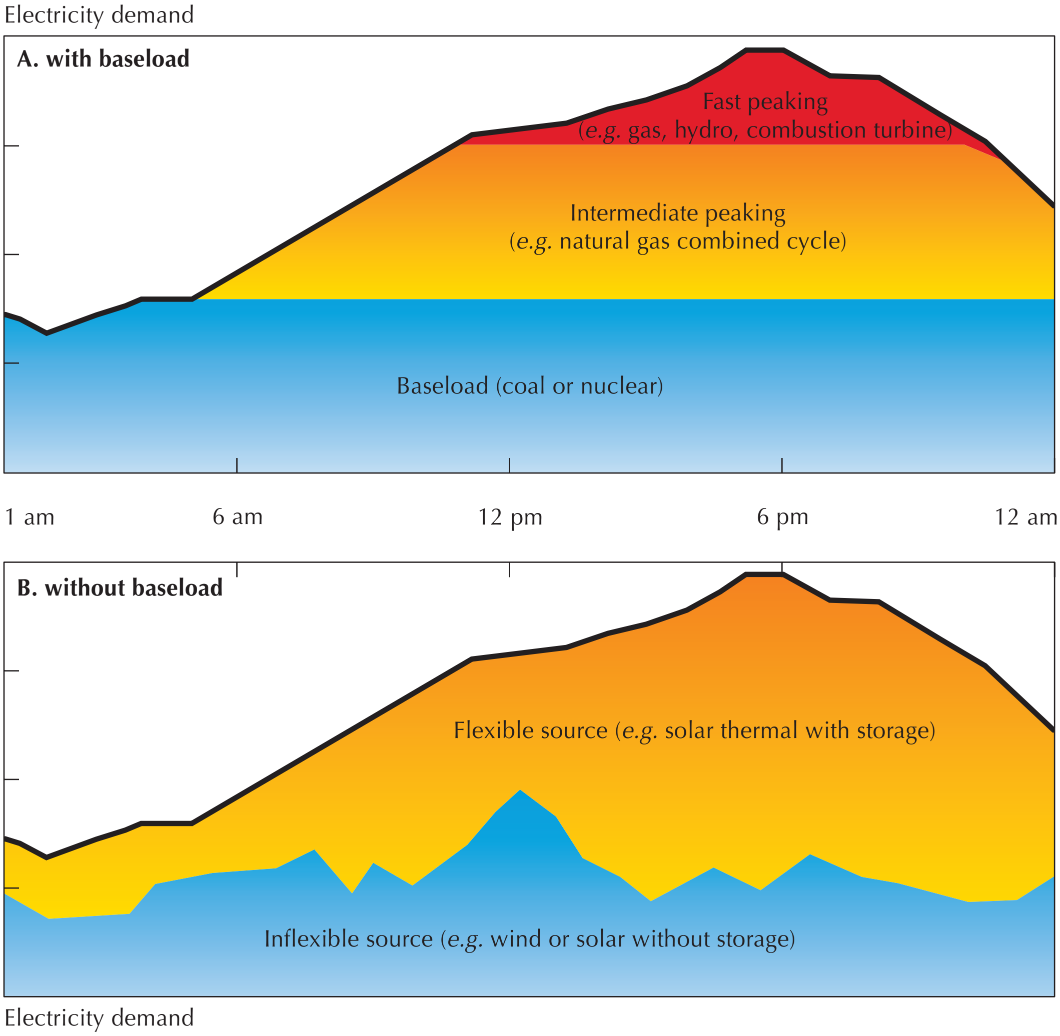
The best available information suggests, however, that the costs of space-based solar power, mostly due to the costs of putting the necessary elements into orbit, would be several orders or magnitude greater than the costs of generating electricity on Earth.

2. *Very long-range electricity transport*

Breakthroughs in superconductive electricity technology could make very long-range electricity transport low cost and loss-free. This would allow countries bathed in daylight to feed solar electricity to those plunged in the night and vice-versa 12 hours later. A more modest version would link countries of both hemispheres over many thousands of kilometres to offset the seasonal variations of the solar resource. Countries in summertime would feed those in wintertime. Even if the reciprocal nature of this option alleviated all energy security concerns, the emergence of affordable, loss-free, very long-range electricity transportation rests on hypothetical technology breakthroughs.

In hot and dry regions or countries suitable for STE from CSP plants, technically solar energy could generate the bulk of the electricity – and possibly even more electricity than locally needed, so some could be exported to nearby, less sunny regions. The match between resource availability and peak demands, whether on a seasonal or daily timescales, is often good in high-DNI countries, being driven by activities and air-conditioning loads. In some of them the electricity demand is today driven in part by lighting, and peaks occur at night. But variability of the solar resource would be addressed with thermal storage, which is both cheap and efficient, with more than 95% round-trip efficiency. Night time is thus not a problem for well-designed CSP plants. Back-up for these plants would be needed to cover only unusually long bad weather conditions. In these sunny regions CSP plants are expected to be able to deliver competitive electricity by about 2030, depending on the costs of fossil fuels and the price attributed to CO_2 emissions. With thermal storage, the usual distinction between peak power and base load would become less relevant, as flexible solar thermal electricity could at all times complement inflexible variable renewables (Figure 11.2). Recent analysis suggests that an average of two to four hours of storage in solar electricity plants in the United States would be enough to run the electricity system of that country on very high proportions (93% to 96%) of solar and wind (Mills and Cheng, 2011*a*).

Figure 11.2 **Base load *versus* load-matching**



*Source: Mills and Cheng, 2011*b.

Key point

Base load concept may not survive very high penetration of renewables.

In sunny countries with lower DNI, costs of photovoltaic electricity would not be a limiting factor, but variability would be, unless non-concentrating solar thermal electricity takes off. In most cases hydro power offers significant potential in such countries, usually of wet climate conditions. Fully-flexible hydro power would balance inflexible PV production.

In less sunny countries, both costs and variability could be limiting factors, calling for a relatively smaller contribution of solar electricity – mostly or exclusively PV. Electricity imports from sunnier regions could significantly raise this contribution, as the difference in solar resource is likely to cover electricity transportation costs over significant distances. The Desertec Industrial Initiative aims to provide Europe with 15% of its electricity, mostly from solar plants in North Africa. However, greater share of imports would likely raise or increase concerns about energy security.

Importantly, this chapter does not offer a modelling exercise showing the least-cost combination. Such modelling would draw supply cost curves, with changes in marginal costs as each type of technology increases its share in the mix. What makes the simplified picture offered here still relevant, though necessarily less precise and conclusive, is the fact that when it comes to solar and wind, the technical potentials are much greater than the projected uses. This means that over time the deployment-led cost reductions will not tail off due to exhaustion of the low-cost resource. Another consequence is that the potentials for solar and wind are not limited by the resource but rather by the demand – or the costs of addressing their variability over time, which increase with their shares in the electricity and energy mixes.

Variability

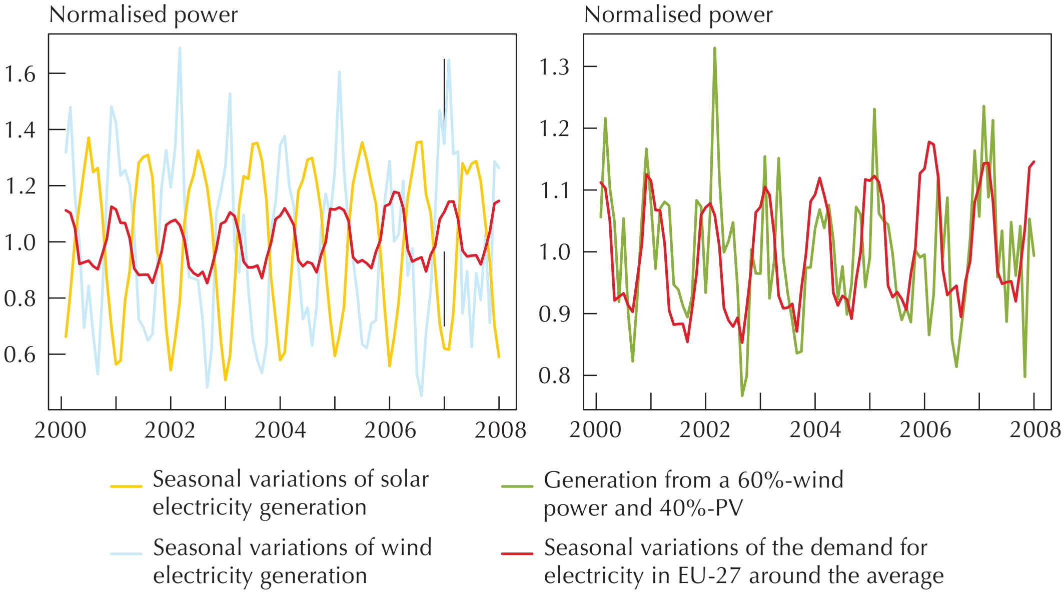
Large seasonal electricity storage, when not provided at low cost by reservoirs for hydropower, would be tremendously expensive. Thus, the electricity mix would largely depend on the seasonal variations in the availability of the various resources, and demand variations. Storage would thus be required mostly on a daily basis to offset rapid variation of the generation of variable renewables when renewables constitute a large proportion of the mix.

In hot, sunny but humid regions with lower DNI, and cold, not-too-sunny but usually windy regions, the match between resource availability and peak demand is also usually good, on both seasonal and daily timescales. For example, whether suitable for CSP or not, Asian countries subject to the monsoon have lower domestic and agricultural (water-pumping) electricity demands during the monsoon months – as well as increased available hydropower. Existing or to-be-developed hydropower plants would likely provide a large part of the balancing needs, as suggested by the example of Brazil and the considerable hydropower potential of central Africa.

Sunny countries will host most of the forthcoming growth in population and activities. Larger countries such as the United States and China have very sunny areas, some with very good DNI, and others with good diffuse irradiance. In the most northern European countries, northern Canada and eastern China, which still represent a significant share of current economy and energy consumption, the variability of the solar resource requires specific solutions, and the optimal energy mix is likely to include a great variety of resources.

Wind power, more abundant in winter, is likely to play an important role as demand peaks in winter in cold countries, although this may change over time. Demand for air-conditioning may increase and demand for heat decrease, resulting from better building insulation, improved standards of living, and climate change. In Europe today, a combination of 40% PV and 60% wind power – whatever their share in the overall electricity mix – would closely match the seasonal variations of electricity demand (Figure 11.3).

Figure 11.3 **Seasonal variations of the European electricity demand and of the electricity generation from solar, wind, and a 60%-wind 40%-PV generation mix**



Note: The average values are normalised to 1.

Source: Heide et al. *2010.*

Key point

Wind power is abundant in winter; PV electricity is abundant in summer.

Daily variations in the generation of electricity from both PV and wind are important to consider. Large penetration rates of wind power and PV would likely require large storage capacities, on top of the flexibility factors considered in Chapter 3 (see Box: Harnessing Variable RE on page 41). Electricity storage would have two related, but somewhat distinct objectives: i) to minimise curtailment of renewable electricity; and ii) to help meet demand peaks. Although electricity shortages do not have to be avoided at any cost, the history of shortages suggests there is a significant value in avoiding them. By contrast, some curtailment of either wind power or PV power might be acceptable as long as the economic losses it entails are lower than the marginal costs of additional storage capabilities only rarely needed, such as in the rare event of simultaneous large PV and large wind power generation.

To assess storage needs, one must make some assumptions relative to generating capacities other than solar. For example, one may consider a global generation of 25 000 TWh from wind power. Wind power has very large technical potential and its costs will likely be lower than, or similar to, most alternatives, *i.e.* in a range of USD 50/MWh to USD 100/MWh in the long run, depending on the shares of on-shore and offshore wind farms and the actual learning curve of offshore wind power. Hydropower and geothermal electricity are more limited by geography. It is assumed that hydropower plus tidal and other marine energies would provide 10 000 TWh/year of electricity. Another 2 000 TWh would come from burning natural gas in balancing plants (blended with the 2 000 TWh of solar hydrogen). The remaining 10 000 TWh would come from a mix of base load, solid biomass, fossil-fuel with CCS, geothermal and nuclear plants (Table 11.1 and Figure 11.4).

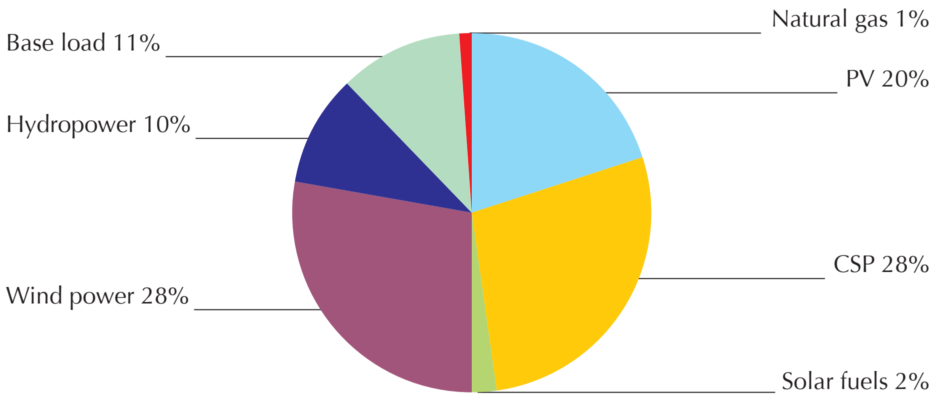
Considering a global electricity generation of 90 000 TWh, slightly less than half could be variable, with an indicative share of 25 000 TWh of wind power (from a global capacity of 10 000 GW), and 18 000 TWh of solar PV from 12 000 GW capacity, plus some tidal power. If there were significant interconnection capacities over vast landmass areas, one can assume a capacity credit[1] of 20% (*i.e.* 2 000 GW) for wind power in winter, 10% (*i.e.* 1 000 GW) in summer.

Table 11.1 **Indicative global capacities and electricity generation**

Technology	Capacity (GW)	Electricity generation (TWh/y)
PV	12 000	18 000
CSP	*6 000	25 000
Solar fuels	**3 000	2 000
Wind power	10 000	25 000
Hydro power and marine	1 600	9 000
Base load (Geothermal, nuclear, solid biomass w. CCS)	1 200	10 000
Natural gas	**3 000	1 000
Total		90 000

** Thermal storage would give CSP plants an average capacity factor of almost 50%. **Shared capacities.*

Figure 11.4 **Global electricity generation by technology in 2060**



Key point

Solar energy could provide half the global electricity generation in 50 years.

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[1] *The capacity credit of renewables, also called capacity value, is the proportion of the rated capacity of installed solar or other renewable plants that can be considered dispatchable. It thus expresses the capacity of conventional power plants that can be displaced by a variable source with the same degree of system security.*

The average capacity demand in regions not suitable for CSP, both hot and humid, and cold regions, would be at most 65 000 TWh divided by the numbers of hours in a year, or about 7 400 GW. This suggests that total demand would vary between 5 000 GW and 10 000 GW. Avoiding curtailment from wind during winter nights could thus require about 5 000 GW of storage capacities (assuming, somewhat implausibly, that all wind power capacities are in these regions). As is shown below, however, batteries of electric vehicles and plug-in hybrids can considerably reduce this need, so the extent of large-scale electricity storage is in fact determined by the requirements to respond to demand peaks.

It is assumed that the overall global demand could reach 10 000 GW at peak time after sunset, giving no capacity credit to PV and only 10%, (*i.e.* 1 000 GW), to wind power (in summer). A mix of base-load plants (geothermal, nuclear, fossil fuels and solid biomass with CCS), would represent a total capacity of 1 200 GW. Flexible hydropower capacities would add 1 600 GW. Imports from CSP-suitable areas could represent an additional firm capacity of 400 GW. Therefore, the total balancing requirement – *i.e.* the additional capacity needed to offset variability of renewables – would be up to about 5 800 GW.

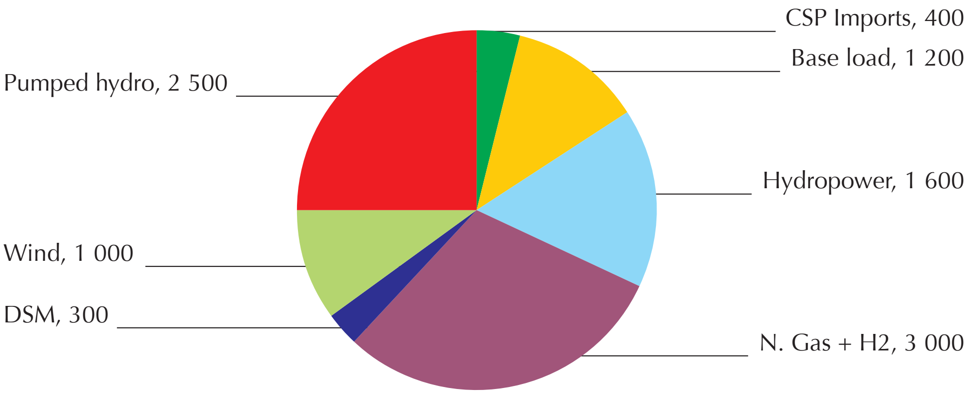
Effective demand-side management (DSM) can reduce balancing needs. It would take advantage of the thermal inertia of many uses of electricity, *i.e.* the fact that heat exchange can be relatively slow, so devices that produce or transfer heat or cold can be stopped for a while without any serious consequence. This inertia will have sharply increased in 50 years by comparison to today, with many heat pumps in buildings and industry, and better insulated equipment (*e.g.* fridges or ovens) and buildings. DSM would also take advantage of the fact that not all electric vehicles need be charged during peak demand. A cautious assessment of 5% reduction from DSM brings the balancing needs down to 5 500 GW.

Only a detailed assessment by continent could identify an optimal breakdown between the two remaining options: gas-fired balancing plants, and storage. Storage capacities are significant investments, and need to be used on a daily basis. Balancing plants cost less in investment but more in fuels – and even if run on a mix of solar hydrogen and natural gas, they would entail CO_2 emissions. They should be used only as extreme peak plants, and in case of contingencies. The optimal mix depends on the amount of electricity needs to be time-shifted on a daily basis to better match the demand. For example, 3 000 GW capacities of balancing plants, running on average 1 000 hours per year, would produce 3 000 TWh per year, of which 2 000 TWh would come from solar hydrogen. The remaining capacity required to respond to demand peaks would be 2 500 GW (Figure 11.5).

The volume of electricity storage necessary to make the electricity available when needed would likely be somewhere between 25 TWh and 150 TWh – *i.e.* from 10 to 60 hours of storage. If 20 TWh are transferred from one hour to another every day, then the yearly amount of variable renewable electricity shifted daily would be roughly 7 300 TWh. Allowing for 20% losses, one may consider 9 125 TWh in and 7 300 TWh out per year.

The same capacities would probably be ample to avoid most PV curtailment during the sunniest hours, usually peak or mid-peak demand hours, assuming low wind speeds at those times. In summertime, when PV production is maximum, a significant part of the storage capacities installed to support wind power will remain unused to store power from wind generation, and thus available to store PV-generated electricity.

Figure 11.5 **Capacities (GW) required at peak demand after sunset with low winds in total non-CSP areas**



Key point

Storage and balancing plants are both needed at peak hours during low-wind nights.

Studies examining storage requirements of full renewable electricity generation in the future have arrived at estimates of hundreds of GW for Europe (Heide, 2010), and more than 1 000 GW for the United States (Fthenakis *et al.*, 2009). Scaling-up such numbers to the world as a whole (except for the areas where STE/CSP suffices to provide dispatchable generation) would probably suggest the need for close to 5 000 GW to 6 000 GW storage capacities. Allowing for 3 000 GW gas plants of small capacity factor (*i.e.* operating only 1 000 hours per year) explains the large difference from the 2 500 GW of storage capacity needs estimated above. However, one must consider the role that large-scale electric transportation could possibly play in dampening variability before considering options for large-scale electricity storage.

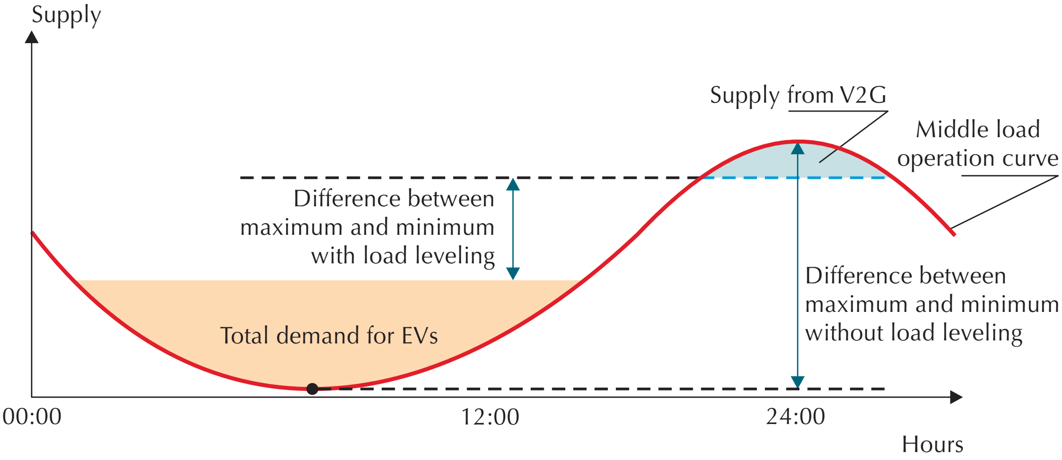
How would G2V and V2G work with both very high penetration of both variable renewable energy sources in the electricity mix, and almost complete substitution by electricity of fossil fuels in light-duty transport? There could be a considerable overall storage volume in the batteries of EV and PHEVs. Assuming 30 kW power and 50 kWh energy capacity for 500 million EVs, and 30 kW power and 10 kWh capacity for 500 million PHEVs worldwide (as in the BLUE Map Scenario), the overall power capacity would be 30 000 GW, the overall energy capacity 30 000 GWh.

Grids-to-vehicles and vehicles-to-grids

Load levelling using the batteries of EVs and PHEVs has been suggested as an efficient way to reduce storage needs, although usually with more modest assumptions relative to the penetration of variable renewables, and much larger balancing capacities from flexible fossil-fuel plants, notably gas plants. They are known as grid-to-vehicle (G2V) and vehicle-to-grid (V2G) options (Figure 11.6).

As one IEA study notes, "one conceptual barrier to V2G is the belief that the power available from the EVs would be unpredictable or unavailable because they would be on the road." It goes on to explain that although an individual vehicle's availability for demand response is unpredictable, the statistical availability of all vehicles is highly predictable and can be estimated from traffic and road-use data. Usually, peak late-afternoon traffic occurs during the peak electricity demand period (from 3 pm to 6 pm). According to United States statistics, even in that period 92% of vehicles are parked and potentially available to the grid (Inage, 2010).

Figure 11.6 **How EV and PHEV batteries can help level the load on the electric grids**



Source: Inage, 2010.

Key point

EVs and PHEVs used with smart grids can help integrate variable renewable electricity.

What is more likely to reduce the power capacity of a billion dispersed batteries is the capillary nature of electric distribution systems. Although recharging stations and high-volume access points may develop fast-charging capabilities going up to 30 kW or even higher, the electrical hook-ups for most batteries may have a much more limited capacity – only 3 kW to 12 kW – to exchange with the grid. Even so, with an assumed average of 6 kW and 90% batteries available for charge, the power capacity available for avoiding curtailment would be 5 400 GW worldwide, more than the 5 000 GW maximum excess supply from variable renewable, estimated above as the difference between maximum wind capacity and base load.

The estimated electricity consumption for all these vehicles over a year would be about 10 000 TWh – a 50% increase over the total for electricity and hydrogen in transport in the BLUE Map Scenario. This number suggests that almost all electricity consumption for travel could come from variable renewables through smart grids. Some excess capacity could also be available for EVs and PHEVs to contribute to peak demand and reduce the required storage needs to avoid shortages.

V2G possibilities certainly need to be further explored. They do entail costs, however, as battery lifetimes depend on the number, speeds and depths of charges and discharges, although to different extents with different battery technologies. Car owners or battery-leasing companies will not offer V2G free to grid operators, not least because it reduces the lifetime of batteries. Electric batteries are about one order of magnitude more expensive than other options available for large-scale storage, such as pumped-hydro power and compressed air electricity storage. The cost of batteries in transport is acceptable because the total cost of the on-board stored energy, including the electricity, will presumably not differ much from the cost of gasoline or diesel fuel in ten years from now. It remains to be seen to what extent V2G is to be preferred over large-scale electricity storage options, or whether it should be seen instead as an ultimate resource to avoid black-outs in very rare occurrences.[2] One can assume, though, that the required storage capacities are driven much more by the constraints of responding to peak demand than by the constraints of avoiding curtailment of renewable variables.

Large-scale electricity storage

Technology options for electricity storage are examined in Chapter 3. The primary candidate for very large-scale electricity storage is pumped-hydro. The power capacity of some existing plants might be increased through more frequent use of their existing reservoir capabilities. But many new stations would be necessary to fulfil the storage requirement of a high penetration of variable renewables.

The overall potential offered by natural relief is not precisely known, and not all countries have mountains, but it is probably much larger than the current capacities. Many existing hydropower stations, sometimes already consisting of several successive basins, could be turned into pumped hydro stations. In North America, for example, with 100 metres altitude difference, the lakes Erie and Ontario could provide for 10 GW peaking capacities and very large storage capacities due to their large surface areas. They could offer one of the few affordable seasonal storage options, providing the investment in waterways and pumps/turbines is paid for by daily operations.

New options are also emerging that would allow pumped-hydro stations using the sea as the lower reservoir. One such pilot plant is already in service in the Japanese island of Okinawa (Photo 11.1). Seawater pumped-hydro facilities could be built in many places. Ideally situated sites would allow for a water head of several dozen metres difference between a cliff top basin and sea level.

If mountainous and coastal natural-lift pumped-hydro plants were not sufficient, it is possible to build new plants on the sea, entirely offshore or, more likely, coastal, as this would limit the length of the necessary dykes. The idea is to use dykes to create a basin (Figure 11.7) that is either higher or lower than sea level. The necessarily low water head in such cases, however, would require large water flows. In total the costs for very large seawater plants might be 50% higher than in the cases described earlier, and even higher for smaller plants. Economies of scale are important here, as the storage capacity increases with the square of the dyke lengths, which account for a large share of the costs. Although no such plant exists yet, the concept involves no more than a combination of existing marine technologies. Resistance to corrosion from salty waters, in particular, has been proven for half a century with tidal plants such as La Rance in France.

Because use of pumped-hydro storage to manage variable renewable sources is based on daily operations, it offers a much smaller footprint than ordinary hydro power of similar electric capacities. A global capacity of 2 500 GW pumped-hydro storage for 50 hours would require (assuming standard depths for the basins) less than 40 000 km^2 of surface area, compared to 300 000 km^2 for existing hydropower plants.

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[2] *See Jacobson and Delucchi, 2011*b *for an extensive discussion of the costs of V2G.*

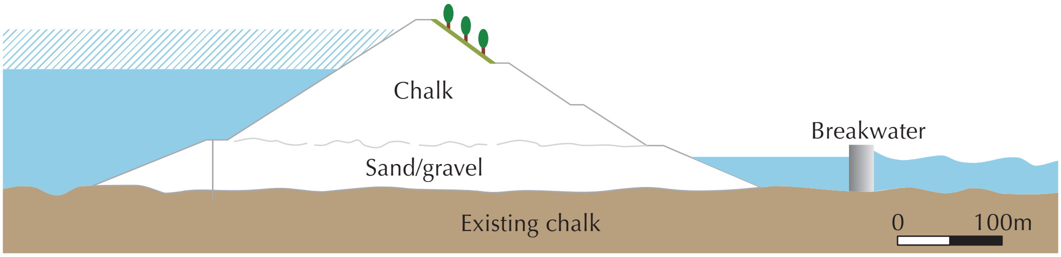
Photo 11.1 **Okinawa's pumped-hydro plant using the ocean as lower reservoir**

Source: J-POWER.

Key point

Many opportunities exist for seawater pumped-hydro plants on the shore.

Figure 11.7 **Sample scheme of a dyke creating an artificial offshore basin in shallow waters for pumped-hydro**



Source: François Lempérière/Hydrocoop.

Key point

Large offshore seawater pumped-hydro plants would cost 50% more than onshore plants.

Investment costs for pumped hydro stations vary from USD 500/kW in the easiest cases to USD 2000/kW for the most difficult cases or coastal marine pumped hydro facilities. Assuming an average cost of USD 1 500/kW with 10% discount rate, investment costs would amount to costs of USD 90/MWh shifted, plus 20% of the generating cost of each shifted MWh to account for the losses (*i.e.* on average USD 20 per MWh shifted). So the total storage cost would be about USD 110/MWh shifted. If the cost of storage is computed with respect to the total variable renewable electricity in the system, it drops to about USD 19/MWh, and USD 13/MWh with respect to the overall electricity generation (out of CSP-suitable zones).

Sound economic decisions, however, focus on marginal costs, *i.e.* the cost of each additional PV or wind power kWh, which must be made dispatchable in systems with already large penetration of renewable, and bear the cost of storage. In sunny regions with more PV than STE/CSP, USD 19/MWh of storage will add to a cost of electricity from PV of less than USD 70/MWh (after 2030). In cold countries, as wind power dominates the mix, the cost of electricity storage will be borne by wind power, and the sum of both costs will remain close to the USD 100/MWh mark.

Other technologies for large-scale electricity storage are compressed-air electricity storage (CAES) and advanced-adiabatic CAES (see Chapter 3). Their deployment first rests on the availability of underground caves suitable for this use. Some analysts assume that large capacities are available (Fthenakis *et al.*, 2009; Delucchi & Jacobson, 2011*a* and *b*), and suggest CAES and AA-CAES will be the key to integrating large amounts of variable electricity in future grids. However, they have not provided evidence for why these options should be preferred over pumped-hydro storage, apart maybe from an implicit preference for storage on the sites of PV or wind power generation.

Footprint of solar electricity

The projected PV capacity in our future "big picture", initially estimated at 12 000 GW, needs to be increased to 15 300 GW to compensate for half the losses in electricity storage (the other half being compensated by wind power). With an average efficiency of 15% and average peak solar irradiance of 1 kW/m^2, this capacity would represent a total module surface area of 100 000 square kilometres. Obviously not all modules would find a space on building roofs and even with many other supporting structures ground-based PV systems will be needed, possibly for two-thirds of the modules. With an appropriate tilt the required surface area, although not necessarily unavailable for other uses, increases by a factor 1.7 at mid-latitudes. The total surface area would thus be 115 000 km^2.

Apart from rooftops, parking lots, farms and other structures, considerable potential rests in "brownfields", *i.e.* areas that have been severely impacted by former industrial activities, whose re-use options are limited by concerns for public health and safety. The US Environmental Protection Agency runs a "brownfields program", siting renewable energy on contaminated land and mine sites. It tracks approximately 490 000 such sites covering about 60 000 km^2.

Another intriguing option is to develop floating PV plants. Such plants could have an increased efficiency with easy one-axis tracking – by simply rotating large floating structures (one revolution per day) supporting PV systems. Projects of this sort are already being considered, in particular on artificial or natural lakes feeding hydro power plants, where they would benefit from existing connecting lines, and would benefit the hydro plants by limiting evaporation. Sceptics, however, point out the cost of floating support structures.

STE/CSP is more efficient than PV per surface of collectors, but less efficient per land surface, so its 25 000 TWh of yearly production would require a mirror surface of 100 000 square kilometres and a land surface of about 300 000 km^2. These areas will, however, be easier to find in arid regions with low or very low population densities and little agricultural activity.

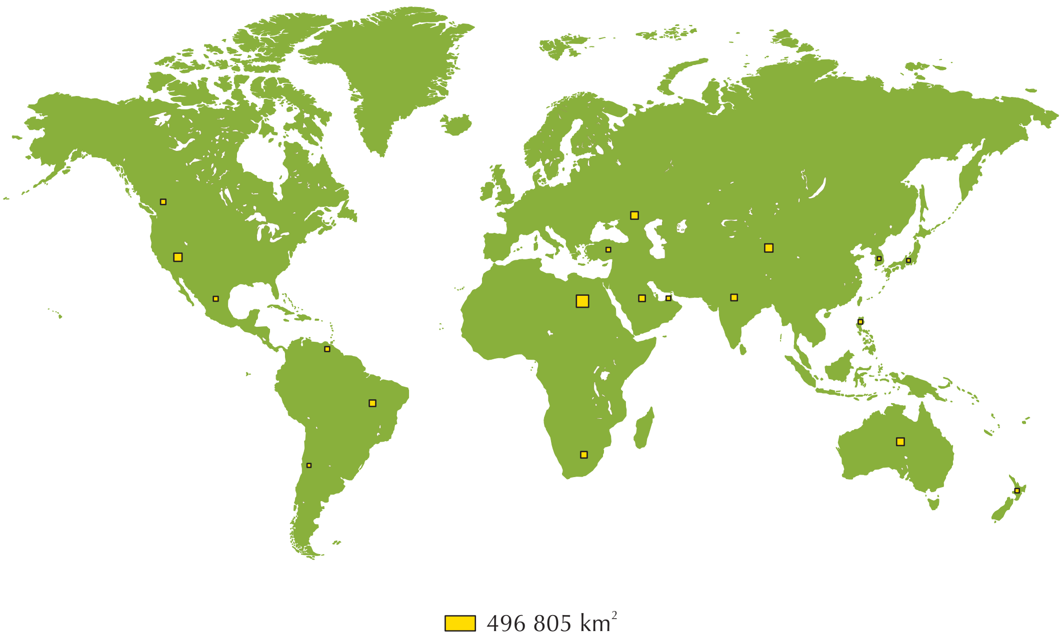
Water availability is unlikely to be a limiting factor for STE/CSP as dry cooling options for steam plants are well-known and fully mature.

In sum, the total of on-ground structures for CSP and PV could be 415 000 km^2 or more (solar fuel generation is not included in these numbers). These are large numbers – 1/360 of all emerged lands. This figure is slightly lower than an independent estimate of the total surface area needed to power the entire world economy by 2030 from solar (Figure 11.8). The availability of land will be a challenge in very densely populated countries, but not on a global scale.

Direct, non-electric energy uses

Besides electricity generation, solar energy can help meet other energy needs: heat and fuel for transport. Direct solar heat could take a share of water and space heating, as well as providing heat to industry and services. Heat pumps would transfer ambient energy, whose origins are solar and geothermal energies, into buildings and some industries. Solar fuels, besides a role in electricity generation, could also provide some heat in buildings and industry; enhance the energy content of biofuels for transport, industry and other uses; and possibly provide some hydrogen for direct uses in various transport systems.

Figure 11.8 **500 000 km^2 of hypothetical on-ground solar plants**



Source: landartgenerator.

Key point

Large-scale deployment of solar energy does not raise global concerns for land use.

How could this translate in numbers? Of the total 140 000 TWh of final energy demand, 50 000 TWh would be direct, non-electric uses of energy, *i.e.* heat in buildings and industry, and transportation. To be clearly distinguished from electric TWh (or "TWh$_e$"), they are all designated below as TWh thermal (TWh$_{th}$), as for both direct use as heat and for transportation purposes they represent the calorific value of the fuel, and not the kinetic energy of transport.

Estimates of the amounts of biomass available for energy purposes vary widely, in relation to land and water needs of agriculture and food production (for opposite views, see *e.g.* Delucchi and Jacobson, 2011*a* and *b*, and Singer, 2011). The *IEA Technology Roadmap: Biofuels for Transport* states that by 2050 it should be possible to provide 9 000 TWh$_{th}$ of biofuels, and about 19 000 TWh$_{th}$ of biomass for heat and electricity from residues and wastes, along with sustainably grown energy crops (IEA, 2011*g*). This division of the estimated total sustainable biomass, however, rests on a model that foresees much less solar and wind generation than this publication, and thus requires larger amounts of biomass to decarbonise the power sector. Biomass might be best employed in the transport sector when lowest possible CO_2 emissions are sought. From the same feedstock, increased by 10% by the use of solar heat in the manufacturing process, one could provide 18 000 TWh$_{th}$ of biofuels, leaving about 8 500 TWh$_{th}$ for heat and power, which is only slightly more than the quantity the industry could absorb by 2050 according to Taibi *et al*. (2010).

Assuming that electricity, with 10 000 TWh$_e$ in transport, displaces three times more combustible fuels, the remaining needs in transport would be about 25 000 TWh$_{th}$, of which 18 000 TWht$_{th}$ will be biofuels, leaving a need for fossil fuels of 7 000 TWh$_{th}$, mostly if not exclusively oil products blended with biofuels for specific quality requirements.

The other 25 000 TWh$_{th}$ would meet heating needs in buildings and especially industry, not covered by electricity and ambient energy through heat pumps. Direct solar heat could likely provide 20% of the total, mostly to heat water and low-temperature processes. This would thus represent 5 000 TWh$_{th}$.

Assuming a capacity factor for solar thermal systems of 1 000 hour per year, 5 000 TWh$_{th}$ of solar heat production would require a thermal capacity of 5 000 GW$_{th}$. An efficiency of 70% and peak solar irradiance of 1 kW/m^2 lead to a required surface area of 7 150 square kilometers, *i.e.* a little less than 1 square meter per inhabitant - an almost trivial figure compared to the 500 000 km^2 required by solar electricity generation (and partially included through hybrid PV-Thermal panels). Direct solar heat would add little to solar energy's footprint.

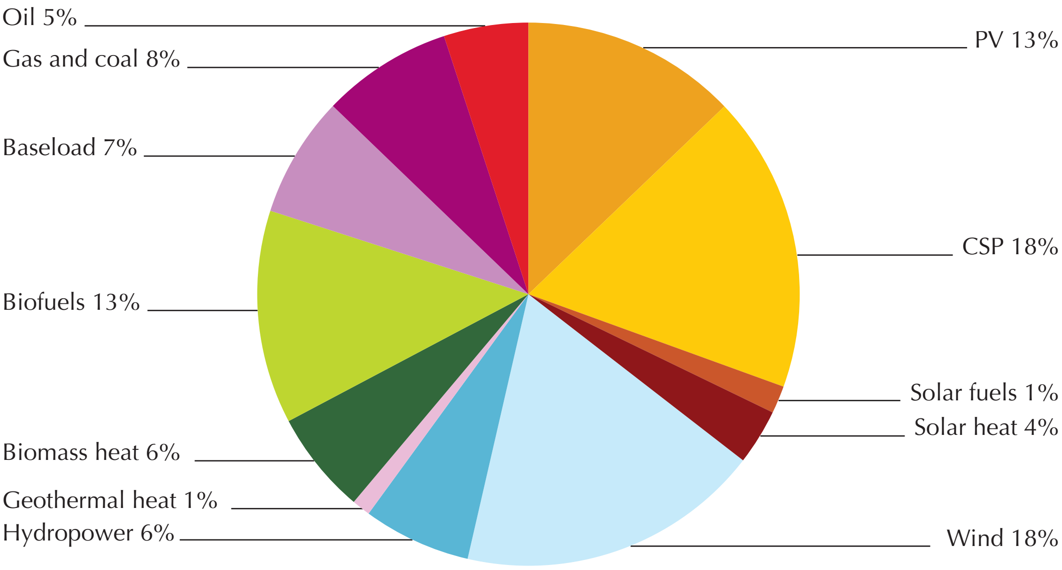
Other renewables would provide significant contributions to heat requirements. The *IEA Technology Roadmap: Geothermal energy* suggests by 2050 a contribution from geothermal heat of 1 600 TWh$_{th}$, which adds to its generation of electricity (IEA, 2011*b*).

In total, biomass, direct solar heat and geothermal heat would provide about 15 000 TWh$_{th}$, leaving room for 10 000 TWh$_{th}$ of fossil fuels, mostly natural gas and coal. Figure 11.9 shows the resulting subdivision of total energy by sources.

CO_2 emissions and variants

CO_2 emissions resulting from this combination can now be assessed. They would result from the generation of 1 000 TWh$_e$ from natural gas in balancing plants, the combustion of 7 000 TWh$_{th}$ of oil products for transport, and, unless CCS is available on a large scale, 10 000 TWh_{th} of a mix of coal and gas in industry – in total, slightly less than 3 Gt CO_2[3] assuming that base load plants (geothermal, nuclear, solid biomass and fossil fuels with CCS) are carbon neutral.

Figure 11.9 **Total final energy by sources, 2060**



Key point

Solar energy could contribute more than a third of total energy needs.

If available, CCS could, however, capture a significant share of these industrial emissions and also capture some of the CO_2 emissions from biomass in industry.

This is only one conceivable combination among others. With respect to the mix of renewables, enhanced geothermal energy may take off after 2020. The hydropower resource may prove different than roughly estimated here, and marine energy may also take off on a much larger scale. Alternatively, lower availability of biomass and hydropower may require even greater investment in wind power and solar power, as well as in electricity storage capacities. Solar fuels may provide more options for heat and transport and not be limited to electricity generation.

Other variants could reduce or increase the need for wind and solar electricity, and associated large-scale electricity storage. Assuming a base load generating capacity of 1 200 GW including nuclear, 100 GW geothermal and some solid-biomass electric plants suggests a role for nuclear somewhere between the Baseline Scenario (capacity 610 GW by 2050, generation 4 825 TWh) and the BLUE Map Scenario (capacity 1 200 GW by 2050, generation 9 608 TWh).

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[3] *Assuming 40% efficiency in the electricity generation by combustion of natural gas and an average emission factor of 270 gCO_2 per kWh for fossil fuels.*

Nuclear power has not been able to considerably expand its basis since the entry into force of the UN Framework Convention on Climate Change in February 1995, despite its recognised value in mitigating energy-related CO_2 emissions. It is not likely to perform much better anytime soon in the post-Fukushima context, but over time it could recover and expand significantly. If it did not, however, solar and wind and associated electricity storage would together have to produce up to 11% more electricity than otherwise, not a considerable change at a global level, if possibly very significant for some countries. Nuclear power as it is now could be substituted by known and proven solar, wind and dispatchable technologies. However, nuclear power might be developed to be more flexible through hydrogen generation in high-temperature nuclear plants. If so, it could substitute economically for gas-fired balancing plants, and/or provide fuels for substituting fossil fuels or biomass in transport and industry. Then it would actually enrich the menu of yet-unproven options for increasing energy security and mitigating climate change, and partially substitute for CCS or solar fuels if they fail to deliver.

In any case, the future will be different from what we can imagine today. History is full of wrong predictions, and this chapter offers no prediction of any kind. It has no other ambition than to illustrate one possible future, among many others. What remains, however, is that a considerable expansion of renewable energy production would serve the goals of energy security, economic stability and environmental sustainability (including climate change mitigation) on a global scale through this century, a conclusion similar to that enunciated by the IPCC Special Report on Renewable Energy (IPCC, 2011). Solar energy in its various forms would likely form the backbone of renewable energy as it is the least limited resource, followed by wind and biomass, then hydropower and others.

Defining primary energy needs

Various methods are used to report primary energy. While the accounting of combustible sources, including all fossil energy forms and biomass, is unambiguous and identical across the different methods, they feature *different* conventions on how to calculate primary energy supplied by non-combustible energy sources, *i.e.* nuclear energy and all renewable energy sources except biomass. In particular, the OECD, the IEA and Eurostat use the physical energy content, while UN Statistics and the IPCC use the direct equivalent method.

For non-combustible energy sources, the physical energy content method adopts the principle that the primary energy form is the first energy form used downstream in the production process for which multiple energy uses are practical. This leads to the choice of the following primary energy forms:

- heat for nuclear, geothermal and solar thermal electricity;
- electricity for hydro, wind, tide/wave/ocean and solar PV.

The direct equivalent method counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, *i.e.* 1 kWh of electricity or heat is accounted for as 1 kWh = 3.6 megajoules (MJ) of primary energy. This method is mostly used in the long-term scenarios literature because it deals with fundamental transitions of energy systems that rely to a large extent on low-carbon, non-combustible energy sources.

Using the direct equivalent method in a scenario with high-level penetration of renewables other than combustible biomass allows comparing the high-level solar "big picture" of this publication with the recent IPCC Special Report on Renewable Energy (IPCC 2011).

Primary energy needs (direct equivalent method) would by 2060 – 2065 be of about 165 000 TWh, under the assumptions of conversion efficiencies of 40% in electricity generation from combustibles, 85% in heat from combustibles, and 60% in manufacturing biofuels, and accounting for losses in electricity storage and in CCS. The contribution of solar energy to these primary energy needs would be about 60 000 TWh[4] or 216 exajoules (Ej). With 36% of primary energy needs (approximately the same share of final energy demand), the solar contribution shown here is significantly higher than the estimates for direct solar energy by 2050 in the scenarios published before 2009 and analysed by the IPCC (2011), though more recent analyses have stretched the possible contribution from solar even higher.

Note that with ambient heat, derived mostly from solar energy (and some geothermal heat), about 30 000 TWh of useful energy is neither taken into account in primary energy needs nor in final energy demand. Taking ambient heat into account, primary energy needs would have to be counted at 195 000 TWh for an overall final energy use of 170 000 TWh. On both accounts, the contribution of solar energy would come close to 50%.

The numbers in this chapter are enough to make one's head spin and may seem unrealistic to many. However, it is the sheer size of the energy system in 50 years from now that is vertiginous. Without a very large application of renewables, the scale of the environmental issues (not just climate change) associated with considerable use of fossil fuels during this century raises the greatest concerns.

The economic burden of making the required energy resources available on such immense scale is hardly less problematic. As the likely convergence of costs of various energy sources around 2030 suggests, the size of the necessary investments, in solar plants, grids, storage facilities, nuclear power plants, oil and gas wells, refineries, coal mines, and power plants, would be roughly similar whatever path is followed.

The energy system of 2065 is almost entirely for us to build. In doing so, we face many uncertainties, but some things are already clear. The future energy system will face many constraints and challenges. In order to cope successfully, the system will need to be widely diverse; no one technology can or should dominate. As it must, such a system will give

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[4] *20 000 TWh from PV (including storage losses), 25 000 TWh STE, 5 000 TWh$_{th}$ solar heat, 6 000 TWh$_{th}$ solar fuels, and 10% of a total primary energy in biomass of 40 000 TWh.*

mankind a great degree of freedom, providing a broad spectrum of readily available technology options for the future generations to choose from as circumstances warrant. To create these options, and make this more sustainable future a true, realistic possibility, we must start now. Effective and cost-effective policies need to be put in place as soon as possible.

Chapter 12
Conclusions and recommendations

The sun offers mankind virtually unlimited energy potential. Only wind power comes close, only biomass is equally versatile. Solar energy can be tapped in many ways, which should be combined to best fulfil the energy needs of the global population and economy. Because it is available all over the planet, it can provide faster access to modern energy services for the disadvantaged communities in rural areas with low population densities. It can also help them meet their energy needs for cooking, displacing ways of using biomass that are often inefficient, unhealthy and not sustainable.

For the bulk of the world population, solar energy can provide inexhaustible and clean electricity in large amounts, only surpassed by wind power in temperate and cold countries. Electricity will be the main carrier of solar energy, displacing fossil fuel use with efficient motors and heat pumps, drawing heavily on solar and geothermal ambient energy.

An integrated approach to the deployment of solar energy needs first to assess and characterise all energy needs, then to identify the smartest possible combination of sources to meet those needs. Wherever possible, passive city and building designs maximising day lighting, solar heat capture (or shielding from excessive solar irradiance) should be preferred. Wherever possible, direct heat should be preferred to more elaborate forms of energy in responding to heat needs. Using ambient energy wherever possible is even better; the only costs are in raising temperature levels.

Similarly, depending on the climatic conditions, effective combinations of solar, wind, geothermal, hydro power and biomass resources will generate ample quantities of clean and renewable electricity. Whether other carbon-free technologies are available or not, an almost complete decarbonisation of electricity generation is possible. Only balancing plants with low capacity factors should have residual CO_2 emissions, which could be further minimised by using solar hydrogen blended with natural gas, unless biogas can also be produced in sufficient amounts.

The most difficult challenges in a future of very low greenhouse gas emissions will be displacing fossil fuels that are in direct uses in industry and transport. But the combination of electricity, mainly from solar and wind, and biomass can reduce fossil fuel usage to quite low levels, while in industry carbon capture and storage (if proven in large-scale applications) should further reduce CO_2 emissions.

Prediction is very difficult, especially about the future, as the great Danish physicist Niels Bohr stated. The exact contribution of solar energy by 2060 and after cannot be known or decided yet. Many other climate-friendly options may appear, and the hopes some put in carbon capture and storage or nuclear may materialise. Efficiency improvements may be faster or slower than expected. Substitution of fossil fuels with electricity may also be faster or slower than anticipated, while hydrogen may play more of a role than foreseen in this publication. Ocean energy and enhanced geothermal energy may become important contributors.

In any case, however, solar energy will play a major role in enhancing energy security, protecting economic stability and ensuring environmental protection, especially mitigating climate change. Developing all available options to draw on this unlimited resource is of utmost importance, if only as an insurance against uncertainties in other technology fields.

Support policies must be broadened, consolidated, strengthened and expanded, whether for a very-high solar future or simply to make full exploitation of solar possible in case other options cannot deliver.

- **Policies need to be broadened**, to fill critical gaps in coverage. Research, development and demonstration need support, especially for those technologies that are the farthest away from market viability, such as solar fuels and solar-enhanced biofuels. Specific incentives are needed to encourage innovation, which most countries have yet to introduce. Solar process heat is very rarely supported or promoted by any government policy, yet its potential is important and its economics often more favourable even than solar space heating.
- **Policies need to be consolidated**, especially those raising cost concerns due to excessive success, such as feed-in tariffs for decentralised on-grid PV deployment. While governments must help the public to understand better what constitutes payment for energy and what is subsidy in the incentives, those must also be adjusted to keep pace with rapidly declining costs, and avoid excessive remuneration levels as markets mature.
- **Policies need to be strengthened**, especially those that have so far provided insufficient incentives, or have defined objectives only vaguely.
- **Policies need to be expanded**, in particular to sunny countries. The renewable energy industry, and especially the solar sector, is fundamentally different from fossil fuels in that the basic energy resource is freely available to all, albeit in varying amounts, and is inexhaustible. Moreover, sunlight cannot be stored without being transformed. If it is not captured when it arrives, it is lost forever. This suggests that the development of equipment to harvest solar energy efficiently and inexpensively should be thought of as a global public good. Literally everyone on the planet stands to benefit if this is accomplished. Like the fight against AIDS, governments should work together in the undertaking, pooling their efforts (and resources) without particular regard to national borders. For example, thought needs to be given to how best to encourage solar energy investment where it would have the greatest impact, *i.e.* in sunny countries. Even very informal discussions of objectives could provide mutual encouragement to governments, sub national authorities and the larger public. International electricity trade, where possible, and financial assistance, in particular in facilitating access to capital, would also help support solar energy deployment in sunny countries.
- For less sunny countries, contributing to solar energy technologies in sunny countries may not be the most direct route to solving their own energy issues. But, it would contribute to making these technologies competitive by stretching limited funds for investment farther, accelerating the learning process, and enabling mass production with greater economies of scale, which would benefit all countries. Efforts to bring solar energy technologies to competitiveness or, at least, affordability will also help increase access to energy and reduce poverty in remote areas, increase global energy security by keeping fossil fuel consumption lower than otherwise, and effectively mitigate climate change.

- The concentration of the recent development of one particular solar technology – photovoltaic – in a small number of countries has brought costs down but raised concerns about policy costs as installations went faster than expected. Probably the best chance to see the risks of unwanted "bubbles" dissipate, while pursuing continuous development till competitiveness, rests in deploying the technology in a greater number of countries and regions. The progressive building-up of solar deployment in the United States, the Chinese decision in July 2011 to implement a feed-in tariff for PV systems, the law to support renewables passed in Japan in August 2011, the ambitious targets announced by Algeria, Chile, India, South Africa and others in the last few months, all suggest this is already happening.

The deployment of solar energy on the scale envisioned requires finding solutions to a particular financing problem, which extends beyond purely economic considerations. By nature, renewable energy technologies are capital intensive and need major up-front investment with long returns. The costs of capital represent a significant share of levelised costs of energy (covering all investment and operational costs over the system lifetime). Emerging technologies are also riskier, although the greater economic risks are linked to the volatility of fossil fuel prices. Technology and market risks increase the cost of capital, making investment into solar energy technologies more expensive, unless governments or long-term investors step in to provide cheaper access to capital.

Efficient support systems, whether feed-in tariffs or power purchase agreement rooted in renewable portfolio standards, are needed to provide long-term secure payments for investments and to reduce capital expenditures. The bulk of solar incentives will be to cover repayment of these capital investments; only a small proportion should be considered subsidies or, rather, learning investments required to bring solar technologies to competitiveness. Their success would provide broad access to an inexhaustible source of energy and help give more than a billion people around the world greater opportunity and economic freedom. By contrast, fossil fuel subsidies only serve to perpetuate a system that is ultimately not sustainable and distributes energy production and its benefits by chance. G20 governments have already committed to eliminate fossil fuel consumption subsidies. They should also consider eliminating production subsidies for fossil fuels. The money spent on these subsidies, estimated USD 312 billion worldwide in 2009 (IEA, 2010*b*) would be much more wisely invested in the development of renewable technologies.

An integrated approach to solar energy deployment should not only concern energy administrations around the world. Its successful implementation will also require a full understanding of the various solar technology options and their implications by all stakeholders, including householders, property owners, architects, city planners, industrialists, transport company executives, local authority officers and officials and many, many others. This requires a deep and prolonged educational effort, to which this publication is aimed at contributing.

Future work

New technology options are constantly emerging. As Edison observed long ago, turning them into productive resources and methods always requires further work ("Genius is one percent inspiration and ninety-nine percent perspiration.") In solar energy, such options include solar fossil hybrids, small-scale solar thermal electricity and solar fuels, and solar-enhanced biofuels. New policy options also emerge, in particular at the international level, from solar electricity trade to other means to link North and South solar deployment and financing.

The IEA is committed to further exploring such options and new combinations, in an open dialogue with interested stakeholders throughout the world. Created in response to a request from the G8 and IEA Ministers, the International Low-Carbon Energy Technology Platform seeks to encourage, accelerate and scale-up action for the development, deployment and dissemination of low-carbon energy technologies – naturally including solar energy. The Technology Platform does this by focusing on practical activities at international, national and regional levels to:

- Bring together stakeholders to catalyse partnerships and activities that enhance the development and implementation of low-carbon energy technology strategies and technology roadmaps at regional and national levels;
- Share experience on best-practice technologies and policies and build expertise and capacity, facilitating technology transition planning that fosters more efficient and effective technology dissemination; and
- Review progress on low-carbon technology deployment to help identify key gaps in low-carbon energy policy and international co-operation, and support efforts to address these through relevant international and regional forums.

Linked to its recognised analytical work, the IEA is also committed to information exchange and policy dialogue beyond its own country membership with emerging economies. With respect to solar energy and renewables, it will naturally work and collaborate with the newly established International Renewable Energy Agency (IRENA) and other interested multilateral organisations. There is no doubt that solar energy will be a major topic for these exchanges in the coming years.

Annex A

Definitions, abbreviations, acronyms and units

Acronyms and abbreviations

AA-CAES	advanced adiabatic compressed-air energy storage
AC	alternating current
AFD	Agence Française de Développement
ASHP	air-source heat pumps
BAPV	building adapted photovoltaic systems
BIPV	building integrated photovoltaic systems
BOS	balance of system
CAES	compressed-air energy storage
CCS	carbon (dioxide) capture and storage
CdTe	cadmium-telluride
CER	certified emission reduction
CIGS	copper-indium-gallium-(di)selenide
CIS	copper-indium-(di)selenide
CLFR	compact linear Fresnel reflector
CoP	coefficient of performance
CPC	compound parabolic collectors
CPV	concentrating photovoltaics
CSP	concentrating solar power
DC	direct current
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
DNI	direct normal irradiance
DRAM	dynamic random-access memory
DSG	direct steam generation
DSSC	dye-sensitised solar cells
EPIA	European Photovoltaic Industry Association
EREC	European Renewable Energy Council
ESTELA	European Solar Thermal Electricity Association
ESTIF	European Solar Thermal Industry Federation
EV	electric vehicles
FCV	fuel-cell vehicles

FIP	feed-in premium
FIT	feed-in tariff
G2V	grid-to-vehicle
GHI	global horizontal irradiance
GNI	global normal irradiance
GSHP	ground-source heat pumps
HTF	heat transfer fluid
HVDC	high-voltage direct-current
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPP	independent power producer
IRENA	International Renewable Energy Agency
ISCC	integrated solar combined cycle
KfW	Kreditanstalt für Wiederaufbau
LCOE	levelised cost of electricity
LFR	linear Fresnel reflector
mc-Si	multi-crystalline silicon
MENA	Middle East and North Africa
MSP	Mediterranean Solar Plan
µc-Si	micro-crystalline silicon
NASA	National Aeronautics and Space Administration
NBSO	New Brunswick System Operator
Ni-Cd	nickel-cadmium
NPS	New policy scenario
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
ONE	Office National de l'Electricité (Morocco)
OPV	organic photovoltaic cells
PCM	phase change materials
PHEV	plug-in hybrid electric vehicles
PJM	Pennsylvania New-Jersey Maryland interconnexion
PPA	power purchase agreement
PV	photovoltaic
PVT	photovoltaic and thermal
R&D	research and development

REC	renewable energy certificate
RPS	renewable energy portfolio standard
SACP	solar-specific alternative compliance payments
sc-Si	single-crystalline silicon
SEI	Stockholm Environment Institute
SEII	Solar Europe Industry Initiative
SHC	solar heating and cooling
SPF	seasonal performance factor
STE	solar thermal electricity
SWERA	Solar and Wind Energy Resource Assessment
SWH	solar water heaters
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNIDO	United Nations Industrial Development Organization
US DOE	United States Department of Energy
V2G	vehicle-to-grid
WRDC	World Radiation Data Center
WSHP	water-source heat pumps
WWF	World Wide Fund for Nature

Units of measure

bbl	blue barrel (159 l of oil)
EJ	exajoules (10^{18} joules)
GW	gigawatts (10^9 watts)
J	joules
kWp	kilowatt of peak capacity
kWh	kilowatt hours
kWh_{th}	kilowatt hours thermal
MJ	megajoule
Mtoe	million tonnes oil equivalent
MW	megawatts (10^6 watts)
MWh	megawatt hour (10^3 kWh)
MWh_{th}	megawatt hour thermal
TWh	terawatt hours (10^9 kWh)
TWh_{th}	terawatt hours thermal
W/m^2	watts per square metre

Annex B
References

A.T. Kearney and ESTELA (European Solar Thermal Electricity Association) (2010), *Solar Thermal Electricity 2025*, A.T. Kearney GmbH, Düsseldorf, Germany, www.estelasolar.eu.

Acket, C. and P. Bacher (2011), "Le scénario Négatep", *Futuribles*, n° 376, Juillet-Août, Paris.

Allen, B. (2009), *Reaching the Solar Tipping Point,* BookSurge, Lexington, KY.

Awerbuch, S. and M. Berger (2003), *Applying Portfolio Theory to EU Electricity Planning and Policy-Making,* IEA/EET Working Paper, OECD/IEA, Paris.

Azar, C. and B. A. Sandén (2011), "The Elusive Quest for Technology-Neutral Policies", *Environmental Innovation and Societal Transitions*, Vol. 1, No. 1, Elsevier, Amsterdam, pp. 135-139.

Bales, C. (ed.) (2005), *Thermal Properties of Materials for Thermo-chemical Storage of Solar Heat,* Report B2 of Subtask B, IEA Solar Heating and Cooling, May, retrieved from http://www.iea-shc.org/publications/downloads/task32-Thermal_Properties_of_Materials.pdf the 12 September, 2011.

Berraho, D. (2010), *Concentrated Solar Power and Water Issues in Middle East and North Africa*, Rapport de stage, AIE - Ecole Polytechnique, Paris.

BMW AG *et al.* (2011), *A Portfolio of Power Trains for Europe: A Fact-Based Analysis*, retrieved from www.zeroemissionvehicles.eu the 12 September, 2011.

Bonnelle D., F. Siros and C. Philibert (2010), "Concentrating Solar Parks with Tall Chimneys Dry Cooling", paper presented at *SolarPACES 2010*, Perpignan, France, 21-24 September.

Bradford, T. (2006), *Solar Revolution: The Economic Transformation of the Global Energy Industry,* MIT Press, Cambridge, MA.

Breyer, C. and A. Gerlach (2010), "Global Overview on Grid-Parity Event Dynamics", presentation at *25th EU PVSEC/WCPEC-5* (25th European Photovoltaic Solar Energy Conference and Exhibition/World Conference on Photovoltaic Energy Conversion), Valencia, Spain, 6-10 September.

Breyer, C., M. Görig and J. Schmid (2011), "Fuel-parity: Impact of Photovoltaics on Global Fossil Fuel-Fired Power Plant Business", presentation at Symposium *Photovoltaische Solarenergie*, Bad Staffelstein, Germany, 3-5 March.

Breyer, C. and J. Schmid (2010*a*), "Global Distribution of Optimal Tilt Angles for Fixed Tilted PV Systems", paper presented at *25th EU PVSEC/WCPEC-5*, Valencia, Spain, 6-10 September, available at www.q-cells.com.

Breyer, C. and J. Schmid (2010*b*), "Population Density and Area Weighted Solar Irradiation: Global Overview on Solar Resource Conditions for Fixed Tilted, One-Axis and Two-Axis PV", paper presented at *25th EU PVSEC/WCPEC-5*, Valencia, Spain, 6-10 September.

Breyer, C. *et al.* (2010), "Reserch and Development Investments in PV: A Limiting Factor for a Fast PV Diffusion?", paper presented at *25th EU PVSEC/ WCPEC-5*, Valencia, Spain, 6-10 September.

Chhatbar, K. and R. Meyer (2011), "The Influence of Meteorological Parameters on the Energy Yield of Solar Thermal Power Plants", paper presented at *SolarPACES 2011*, Grenade, Spain, 20-23 September.

Dias, P. (2011), "Solar Thermal in Europe", presentation at the *IEA Solar Heating and Cooling Roadmap Workshop*, Paris, 28 April.

DLR (Deutsches Zentrum für Luft- und Raumfahrt - German Aeroposace Center) (2005), *Concentrating Solar Power for the Mediterranean Region,* MED-CSP, Final Report, DLR, Institute of Technical Thermodyanmics, Stuttgart, Germany.

Dupeyrat, P., S. Fortuin and G. Stryi-Hipp (2011), "Photovoltaic/Solar Thermal Hybrid Collectors: Overview and Perspective", paper presented at the *5th European Solar Thermal Energy Conference*, Marseille, 19-20 October.

PIA (European Photovoltaic Industry Association) and Greenpeace (2011), *Solar Generation 6*, EPIA, Brussels.

ESTIF (European Solar Thermal Industry Federation) (2007), *Solar Thermal Action Plan for Europe (STAP),* ESTIF, Renewable Energy House, Brussels.

EURELECTRIC (Union of the Electricity Industry) (2004), *Electricity for More Efficiency: Electric Technologies and their Energy Savings Potential*, Brussels.

Faaß, R. (2001), *CRYOPLANE*, *Flugzeuge mit Wasserstoffandtrieb*, Airbus Deutschland GmbH, Hamburg, retrieved from www.fzt.haw-hamburg.de/pers/Scholz/dglr/hh/text_2001_12_06_Cryoplane.pdf the 12 September, 2011.

Fluri, T.P. *et al.* (2009), "Cost Analysis of Solar Chimney Power Plants", *Solar Energy*, Vol. 83, Elsevier, Amsterdam, pp. 246-256.

Forsberg, C.W. (2010), "High-Temperature Salt-Cooled Reactors: Markets and Partners", presentation at *FHR Workshop*, Oak Ridge National Laboratory, Tennessee, 20 September.

Forsberg, C W., P. F. Peterson and Haihua Zhao (2007), "High-Temperature Liquid-Fluoride Salt Closed-Brayton-Cycle Solar Power Towers", *Journal of Solar Energy Engineering*, Vol. 129, No. 2, American Society of Mechanical Engineers (ASME), New York, pp. 141-146.

Fthenakis, V. (2004), "Life Cycle Impact Analysis of Cadmium in CdTe PV Production", *Renewable and Sustainable Energy Reviews*, Vol. 8, N° 5, Elsevier, Amsterdam, pp. 303–334.

Fthenakis, V., J. Mason and K. Zweibel (2009), "The Technical, Geographical, and Economic Feasibility for Solar Energy to Supply the Energy Needs of the US", *Energy Policy*, Vol. 37, N° 2, Elsevier, Amsterdam, pp. 387-399.

France Nature Environment (2011), *Photovoltaïque: énergie renouvelable en danger de disparition,* dossier de presse, 12 janvier, Paris.

de Gouvello, C. and Y. Maigne (eds.)(2002), *Decentralised Rural Electrification*, Systèmes Solaires, Paris.

Greenpeace International, SolarPACES (Solar Power And Chemical Energy Systems) and ESTELA (2009), *Global Concentrating Solar Power Global Outlook 09*, Greenpeace International, Amsterdam.

Haggard, K., D. Bainbridge and R. Aljilani (2009), *Passive Solar Architecture Pocket Reference*, International Solar Energy Society (ISES), Freiburg, Germany.

Heide, D. *et al*. (2010), "Seasonal Optimal Mix of Wind and Solar Power in a Future, Highly Renewable Europe", *Renewable Energy*, Vol. 35 N° 11, Elsevier, Amsterdam, pp. 2483-2489.

Hermann, W. A. (2006), "Quantifying Global Energy Resources", *Energy*, Vol. 31 N° 12, Elsevier, Amsterdam, pp. 1685-1702.

Hoyer-Klick, C. *et al*. (2010), "Technical Implementation and Success factors for a Global Solar and Wind Atlas", paper presented at a workshop of the Multilateral Working Group on Implementing the Major Economies Forum Global Partnership's Technology Action Plans for Wind and Solar Technologies, Madrid, 18 November.

IEA (International Energy Agency) (2006), *Light's Labor's Lost*, OECD/IEA, Paris.

IEA (2008*a*), Price Caps and Price floors in Climate Policy – A Quantitative Assessment, IEA Information Paper, OECD/IEA, Paris, December.

IEA (2008*b*), *Energy Technology Perspectives 2008*, OECD/IEA, Paris.

IEA (2008*c*), *Energy Efficiency Requirements in Building Codes, Energy Efficiency Policies for New Buildings*, IEA Information Paper, OECD/IEA, Paris.

IEA (2008*d*), *Deploying Renewables: Principles for Effective Policies*, OECD/IEA, Paris.

IEA (2009*a*), *Energy Technology Transitions for Industry*, OECD/IEA, Paris.

IEA (2009*b*), *Transport, Energy and* CO_2, OECD/IEA, Paris.

IEA (2009*c*), *IEA Technology Roadmap: Cement Technology*, OECD/IEA, Paris.

IEA (2009*d*), *Cities, Towns and Renewable Energy: Yes in my Front Yard,* OECD/IEA, Paris.

IEA (2010*a*), *Energy Technology Perspectives 2010*, OECD/IEA, Paris.

IEA (2010*b*), *World Energy Outlook 2010*, OECD/IEA, Paris, November.

IEA (2010*c*), *IEA Technology Roadmap: Solar Photovoltaic Energy*, IEA, Paris, May.

IEA (2010*d*), *IEA Technology Roadmap: Concentrating Solar Power*, OECD/IEA, Paris.

IEA (2010*e*), *IEA Technology Roadmap: Smart Grids*, OECD/IEA, Paris.

IEA (2011*a*), *Key Energy Statistics*, OECD/IEA, Paris.

IEA (2011*b*), *IEA Technology Roadmap: Geothermal Energy*, OECD/IEA, Paris.

IEA (2011*c*), *Harnessing Variable Renewables – A Guide to the Balancing Challenge,* OECD/IEA, Paris.

IEA (2011*d*), *IEA Technology Roadmap: Energy-Efficient Buildings: Heating and Cooling Equipment*, OECD/IEA, Paris.

IEA (2011e), *IEA Technology Roadmap: Electric and Plug-in Hybrid Electric Vehicles,* OECD/IEA, Paris.

IEA (2011*f*), *Climate and Electricity Annual: Data and Analyses*¸ OECD/IEA, Paris.

IEA (2011*g*), *IEA Technology Roadmap: Biofuels for Transport*, OECD/IEA, Paris.

IEA (2011*h*), *Deploying Renewables 2011*, OECD/IEA, Paris.

IEA (forthcoming), *IEA Technology Roadmap: Solar Heating and Cooling*, OECD/IEA, Paris.

IEA-PVPS (IEA Photovoltaic Power Systems Programme) (2002), *Potential for Building Integrated Photovoltaics*, Report IEA-PVPS T7-4, St. Ursen, Switzerland.

IEA-SHC (IEA Solar Heating and Cooling) (2000), *Daylight in Buildings A Source Book on Day Lighting Systems and Components*, IEA-SHC, www.iea-shc.org/task21/source_book.html.

IEA-SHC (2008), *Process Heat Collectors*, W. Weiss and M. Rommel (eds), IEA-SHC Task 33 and IEA SolarPACES Task IV: Solar Heat for Industrial Processes, AEE INTEC, Gleisdorf, Austria.

Inage, S. (2009), *Prospects for Large-Scale Energy Storage in Decarbonised Power Grids*, IEA Working Paper, OECD/IEA, Paris.

Inage, S. (2010), *Modelling Load Shifting Using Electric Vehicles in a Smart Grid Environment*, IEA Working Paper, OECD/IEA, Paris.

IPCC (Intergovernmental Panel on Climate Change) (2001), "The Climate System: an Overview", in *Climate Change 2001: The Scientific Basis, Report from Working Group I,* Cambridge University Press, Cambridge, UK.

IPCC (2007), *Climate Change 2007, Synthesis Report - Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, [Core Writing Team, R.K. Pachauri and A. Reisinger, (eds)], IPCC, Geneva, Switzerland.

IPCC (2011), *Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer *et al.* (eds)], Cambridge University Press, Cambridge, UK.

ISCCP Data Products (2006), *International Satellite Cloud Climatology Project* (ISCCP) isccp.giss.nasa.gov/projects/flux.html.

Jacobson, M. Z. and M. A. Delucchi (2011*a*), "Providing all Global Energy with Wind, Water, and Solar Power, Part I: Technologies, Energy Resources, Quantities and Areas of Infrastructure, and Materials", *Energy Policy,* Vol. 39 N° 3, Elsevier, Amsterdam, pp. 1154-1169.

Jacobson, M. Z. and M. A. Delucchi (2011*b*), "Providing all Global Energy with Wind, Water, and Solar Power, Part II: Reliability, System and Transmission Costs, and Policies", *Energy Policy,* Vol. 39 N° 3, Elsevier, Amsterdam, pp. 1170-1190.

Liébard, A., M. Rodot et C. Philibert (1990), *Du Neuf sous le soleil*, Calmann-Lévy/Systèmes Solaires, Paris.

Malbranche, Ph. et C. Philibert (1993), *L'énergie solaire et la protection de l'environnement*, UNESCO, Paris.

Martin, C.L. and Y. Goswami (2005), *Solar Energy Pocket Reference*, ISES, Freiburg, Germany.

Meier, A. and C. Sattler (2009), *Solar Fuels from Concentrated Sunlight*, Richter, C. (ed.), IEA SolarPACES, Tabernas, Spain.

Meyer, R. (2011), *CSP Today Technical Top Tips - Solar Resource Assessment,* mimeo, Suntrace GmbH, Hamburg, Germany.

Mills, D. and W. Cheng (2011*a*), *Running the USA from Wind and Solar*, paper presented at ISES World Solar Congress, 28 August – 2 September, Kassel, Germany.

Mills, D. and W. Cheng (2011*b*), *Baseload and Inflexibility*, paper presented at ISES World Solar Congress, 28 August – 2 September, Kassel, Germany.

Nemet, G.F. (2006), "Beyond the Learning Curve: Factors Influencing Cost Reductions in Photovoltaics", *Energy Policy*, Vol. 34 N° 17, Elsevier, Amsterdam, pp. 3218-3232.

Nicolas, F., J.-P. Traisnel et M. Vaye (1974), *La face cachée du Soleil*, Ecole Nationale Supérieure d'Architecture de Grenoble, Paris.

Palz, W. (ed.) (2011), *Power for the World: The Emergence of Electricity from the Sun*, Pan Stanford Publishing Pte. Ltd., Singapore.

Perkins, C. and A.W. Weimer (2009), "Perspective - Solar-thermal Production of Renewable Hydrogen", *AIChE Journal*, Vol. 55 N° 2, pp. 286-293.

Pharabod, F. et C. Philibert (1991), *Les centrales solaires LUZ*, Comité d'action pour le solaire, Paris.

Philibert, C. (2005), *The Present and Future Use of Solar Thermal Energy as a Primary Source of Energy*, The Interacademy Council, Amsterdam.

PwC (PricewaterhouseCoopers LLP) *et al.* (2010), *100% Renewable Electricity: A Roadmap to 2050 for Europe and North Africa*, PwC, London.

Raghavan, S.V. *et al.* (2010), *Harnessing Solar Energy: Options for India*, Center for Study of Science, Technology and Policy (CSTEP), Bangalore, India.

Ruiz, V. (ed.) (2010), *La electricidad termosolar, historia de éxito de la investigacion, (Solar Thermal Power: History of a Research Success)*, Protermosolar, Madrid, Spain.

Schlaich, J. and M. Robinson (1995), *The Solar Chimney: Electricity from the Sun*, Axel Menges GmbH, Stuttgart, Germany.

Shere, J. (2011), *Renewable*, a book-in-progress about renewable energy, retrieved from http://renewablebook.com the 12 September 2011.

Singer, S. (2011), *The Energy Report: 100% Renewable Energy by 2050*, WWF (World Wide Fund for Nature), Ecofys, and OMA (Office for Metropolitan Architecture), Gland, Switzerland.

Smil, V. (2006), *Energy at the Crossroads*, Background notes for a presentation at the *OECD Global Science Forum Conference on Scientific Challenges for Energy Research*, Paris, 17-18 May.

Steinfeld, A. and R. Palumbo (1998), "Fuels from Sunlight and Water", *Sun at Work in Europe*, Vol. 12, No. 2, pp. 8-10.

Steenblick, R. (2006), "Liberalising Trade in Renewable-Energy Products and Associated Goods", *OECD Trade Policy Studies, Environmental and Energy Products, The Benefits of Liberalising Trade*, OECD, Paris.

Stine, W.B. and M. Geyer (2011), *Power from the Sun,* retrieved from www.powerfromthesun.net the 12 September 2011.

Taibi, E. and D. Gielen (2010), *The Potential for Renewable Energy in Industry by 2050*, presentation at the IAEE European Conference 2010, Vilnius, Lithuania, August.

Taibi, E., D. Gielen and M. Bazilian (2010), *Renewable Energy in Industrial Applications - An Assessment of the 2050 Potential*, UNIDO (United Nations Industrial Development Organisation), Vienna.

Tardieu Alaphilippe, M. (2007), *Recherche d'un nouveau procédé de conversion thermodynamique de l'énergie Solaire, en vue de son application à la cogénération de petite puissance*, thèse présentée à l'Université de Pau et des Pays de l'Adour, Pau, France.

Teske, S., (2008) *Energy Revolution*, EREC (European Renewable Energy Council) and Greenpeace, retrieved from www.energyblueprint.info the 12 September 2011.

Vorayos, N., T. Kiatsiriroat and N. Vorayos (2006), "Performance Analysis of Solar Ethanol Distillation", *Renewable Energy*, Vol. 31 N° 15, Elsevier, Amsterdam, pp. 2543-2554.

Weiss, W. and F. Mauthner (2011), *Solar Heat Worldwide: Markets and Contributions to the Energy Supply 2009*, IEA Solar Heating and Cooling Programme, AEE Intec, Gleisdorf, Austria.

Welle, R. (2010), "Stone Storage", presentation at the *4th CSP Summit*, San Francisco, 25 June.

Weiss, W. (2011), Solar Thermal, "State of the art, Application Areas and Preview of Technology Development", presentation at the *IEA Solar Heating and Cooling Roadmap Workshop*, 28-29 April, Paris.

Werner, S. (2005-2006), *The European Heat Market,* Work package 1, Final Report, Euroheat & Power, Brussels.

Wright, M. and P. Hearps (2010), *Zero Carbon Australia Stationary Energy Plan* (2010), Energy and Research Institute, the University of Melbourne, Victoria, Australia.

Zervos, A., C. Lins and J. Muth (2010), *Re-Thinking 2050: A 100% Renewable Energy Vision for the European Union*, European Renewable Energy Council, Renewable Energy House, Brussels.

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